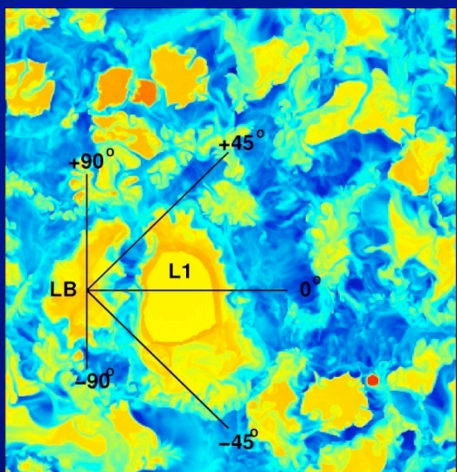
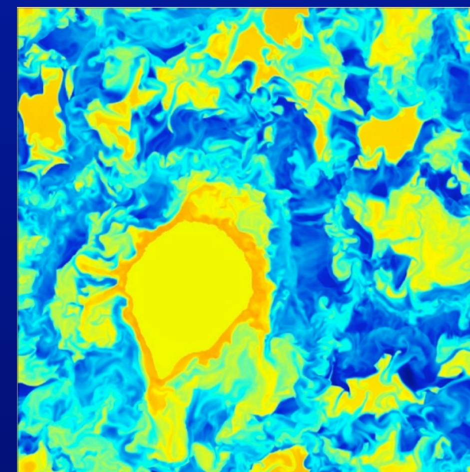
Modelling the Local Warm Bubble



"*The History and Future of the Local And Loop I bubbles*" – Breitschwerdt & Avillez 2006, A&A Letters **452**, 1



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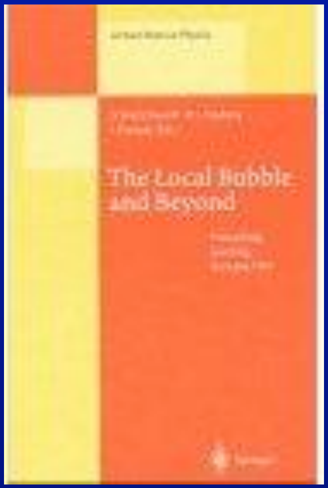
Overview

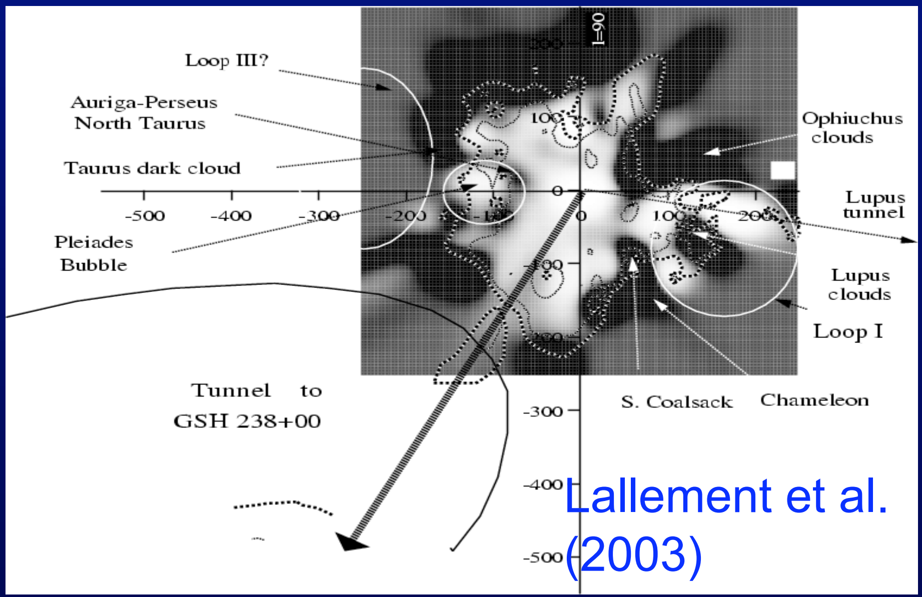
- Introduction
- Some important facts about the ISM
- Origin of the LB – Search for the Smoking Gun
  - Moving groups
  - Complete search of local volume
- Results: 3D AMR Simulations
- Summary & Conclusions

1. Introduction



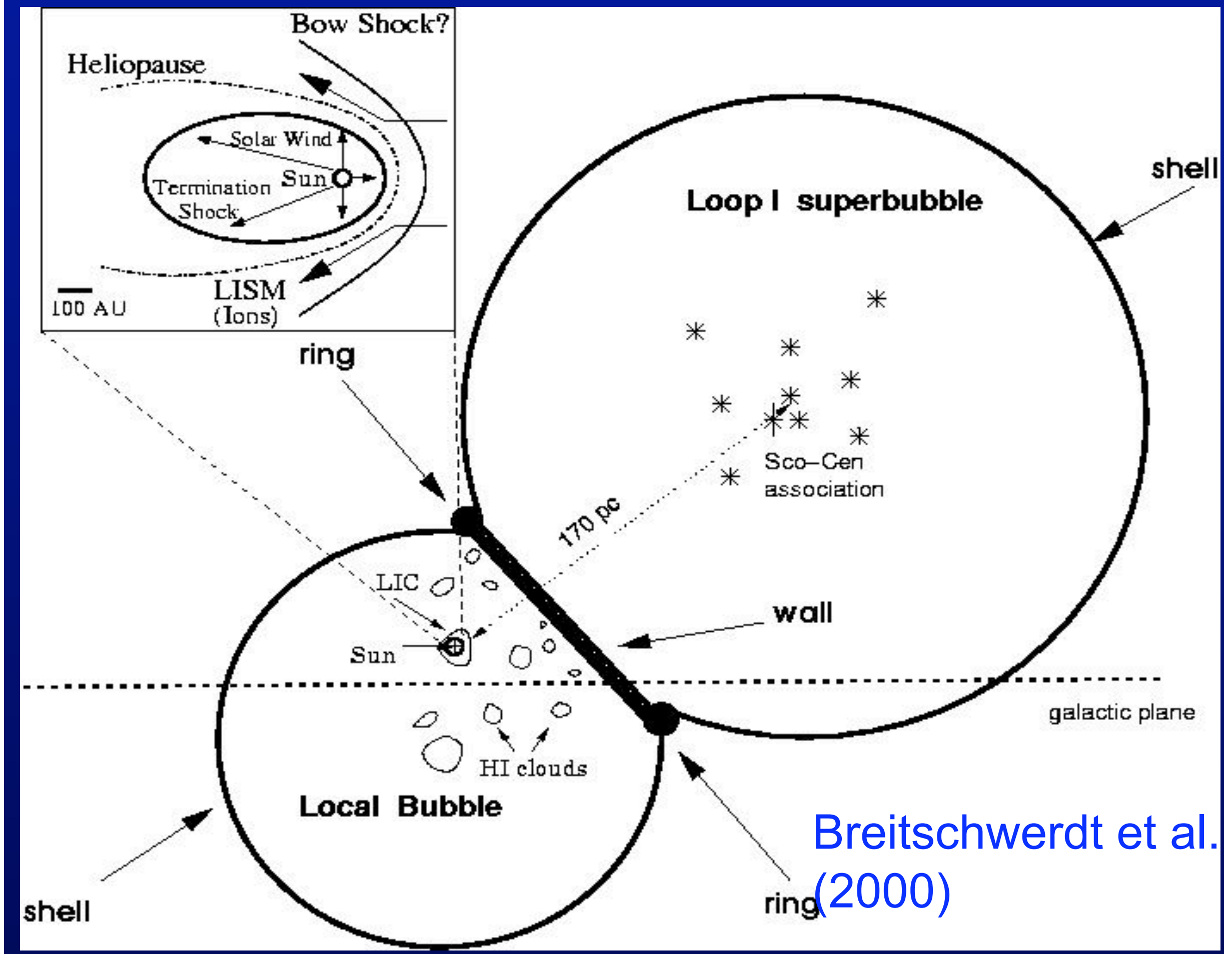
What do we know about the LB for sure?

Region of very low HI density
- Local emission of soft X-rays
- Low OVI column density
- Low pressure of local cloud: $P/k \sim 2000\ \mathrm{K\ cm^{-3}}$
- Probably open toward NGP
- Probably interacting with Loop I



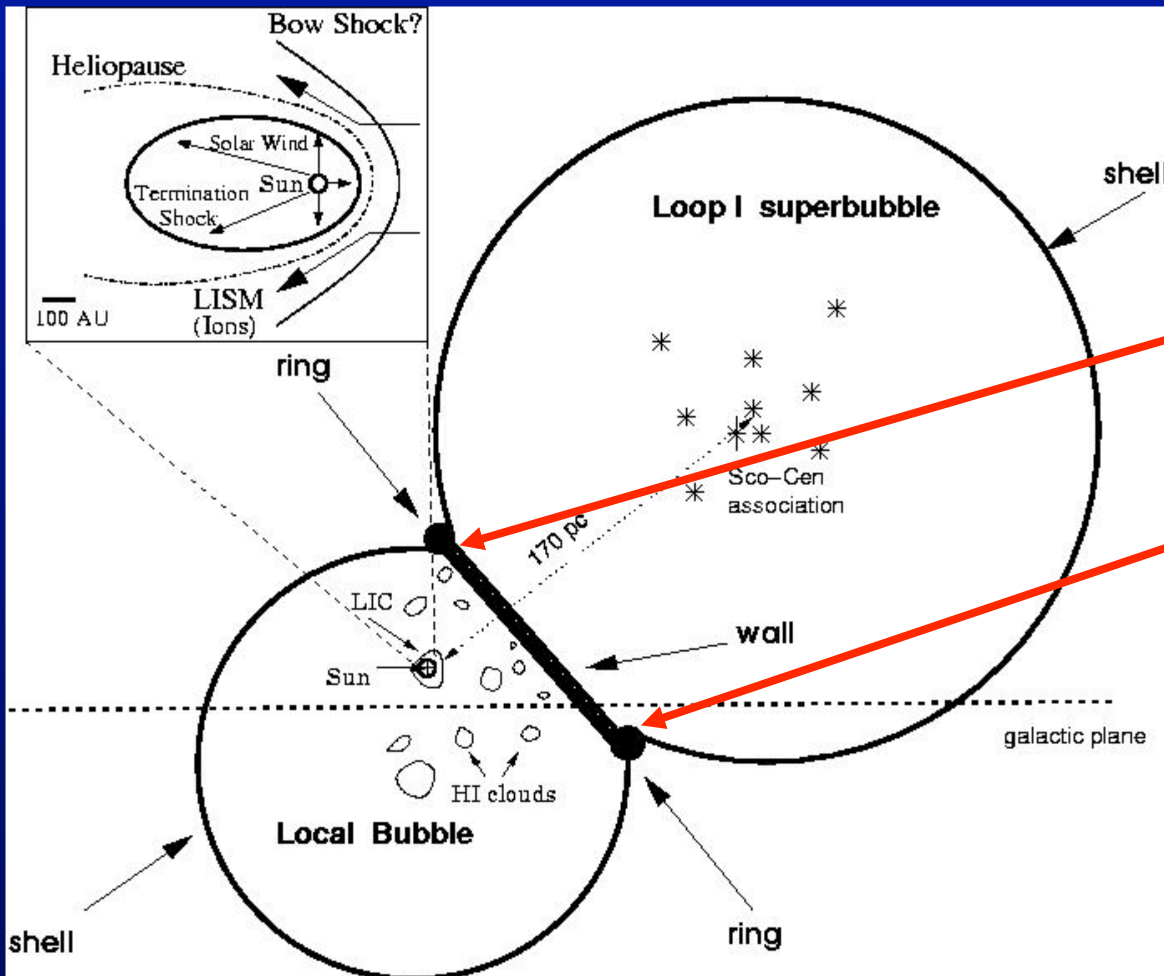
Lallement et al. (2003)

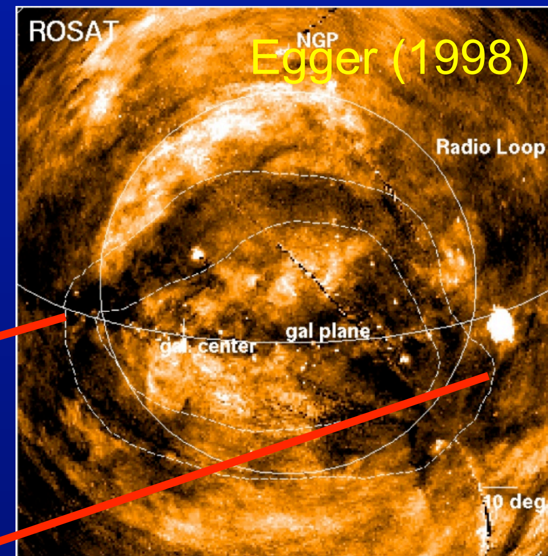
Sketch of LISM

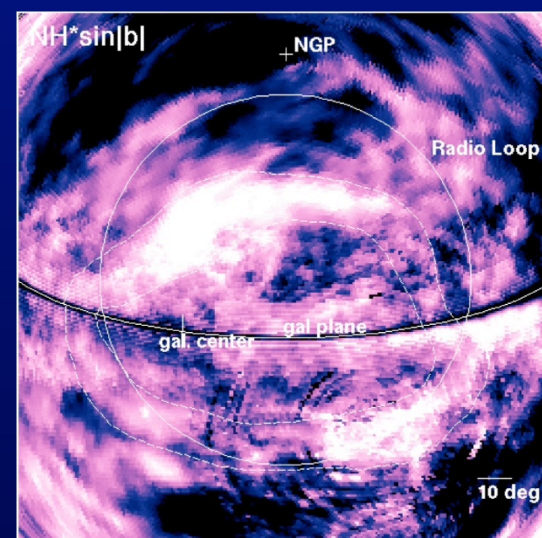


- Solar System and heliosphere embedded in Local Cloud (LIC): $T \approx 6700$ K, $R \approx 2$ pc, $n \approx 0.1\ cm^{-3}$
- Local Bubble is our cosmic interstellar habitat: $T \approx 10^6$ K, $R \approx 100$ pc, $n \approx 5\ 10^{-3}\ cm^{-3}$???
- bubbles are embedded in a general SN driven ISM!
- LB is interacting with an adjacent bubble

Local Bubble & Loop I

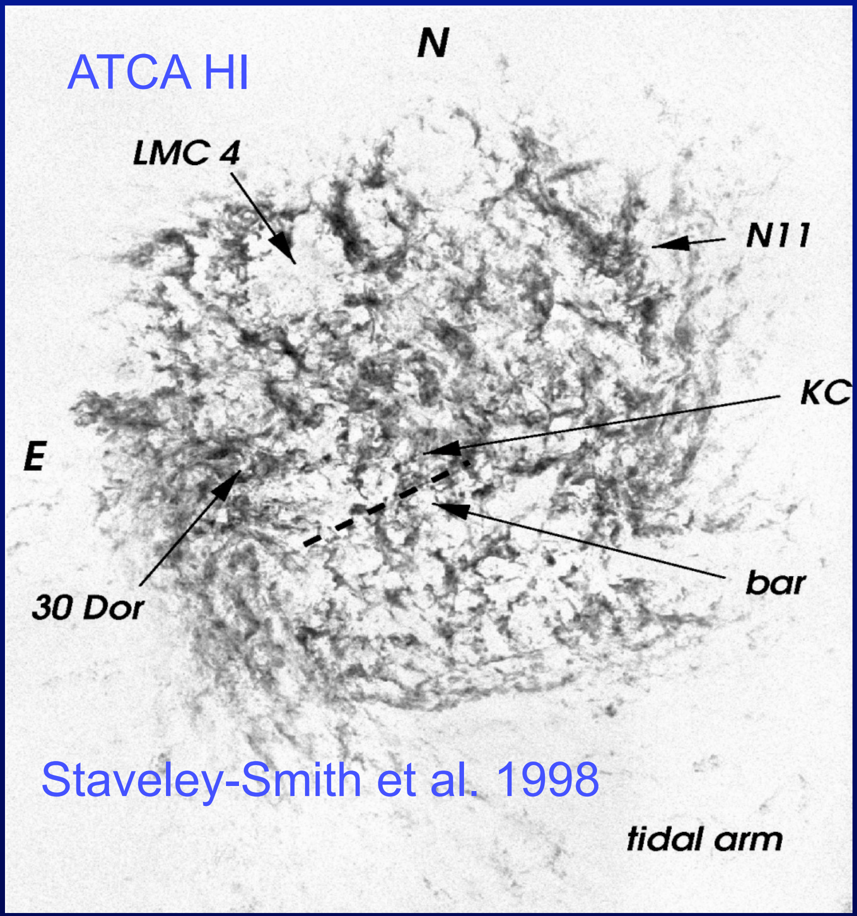






LB and Loop I are interacting bubbles!

2. Some facts to remember about the ISM – how does it evolve?



- Low resolution: ISM appears smooth and distributed into distinct phases: molecular (MM), cold (CNM), warm (WNM + WIM: neutral + ionized), hot (HIM)
- High resolution: ISM is frothy, filamentary, fractal, not in pressure equilibrium, turbulent (supersonic, superalfvénic)

Models like 3-phase (McKee & Ostriker 1977) and "chimney" model (Norman & Ikeuchi 1989) capture some structure but not the essential physics!

- Reynolds Number is high: $\mathrm{Re} = \frac{uL}{\nu} \approx 3\times10^{3} M\ L\left[pc\right] n\left[cm^{-3}\right]$

  i.e. $10^5 - 10^7$ (Elmegreen & Scalo 2004); M=u/c … Mach number

→ ISM is highly turbulent and compressible!
(predicted already by v. Weizsäcker, 1951)

- Possible driving sources:
  - stellar: HII regions, stellar winds, supernovae (SNe), superbubbles (SBs)
  - galactic rotation
  - self-gravity
  - fluid instabilities: RT-, KH-, Parker instability, MRI etc.
  - MHD: streaming instability (cosmic rays)

SNe dominate energy input in spirals (Mac Low & Klessen 2004):

$$\frac{dE}{dt} \cong -\frac{1}{2}\rho\frac{v_{rms}^3}{L_0} \approx 3\times10^{-26}\left(\frac{\eta_{SN}}{0.1}\right)\left(\frac{\sigma_{SN}}{1\mathrm{SNu}}\right)\left(\frac{H_c}{100\mathrm{pc}}\right)^{-1}\left(\frac{R_{SF}}{15\mathrm{kpc}}\right)^{-2}\left(\frac{E_{SN}}{10^{51}\mathrm{erg}}\right)\ \mathrm{erg\ cm^{-3}\ s^{-1}}$$

Modeling a SN driven ISM

Things to remember:

- choose a “representative” patch of the ISM
  - large enough to be not severely influenced by BC’s
  - small enough to put on a grid with sufficient resolution
- choose a sufficiently large extension perpendicular to the disk to capture disk-halo-disk circulation flows
- Evolution time: results should not depend on initial set-up: erase “memory effects”

Philosophy: “bottom-up” model

- include most important physical processes step by step
- focus on the most important ones:

  → heating and cooling

  → gravitational potential by stars (self-gravity underway)

  → galactic magnetic field and its evolution

High Resolution Simulations

- Solve full-blown HD/MHD equations on a *large grid: 1 kpc × 1kpc × ± 10 kpc* (Δx=0.625 pc)
- Type Ia,b/II SNe: random + clustered (~60%), IMF
- Background heating due to diffuse UV photon field
- SFR ∝ local density/temp.: $n > 10\ cm^{-3}$/$T < 100$ K

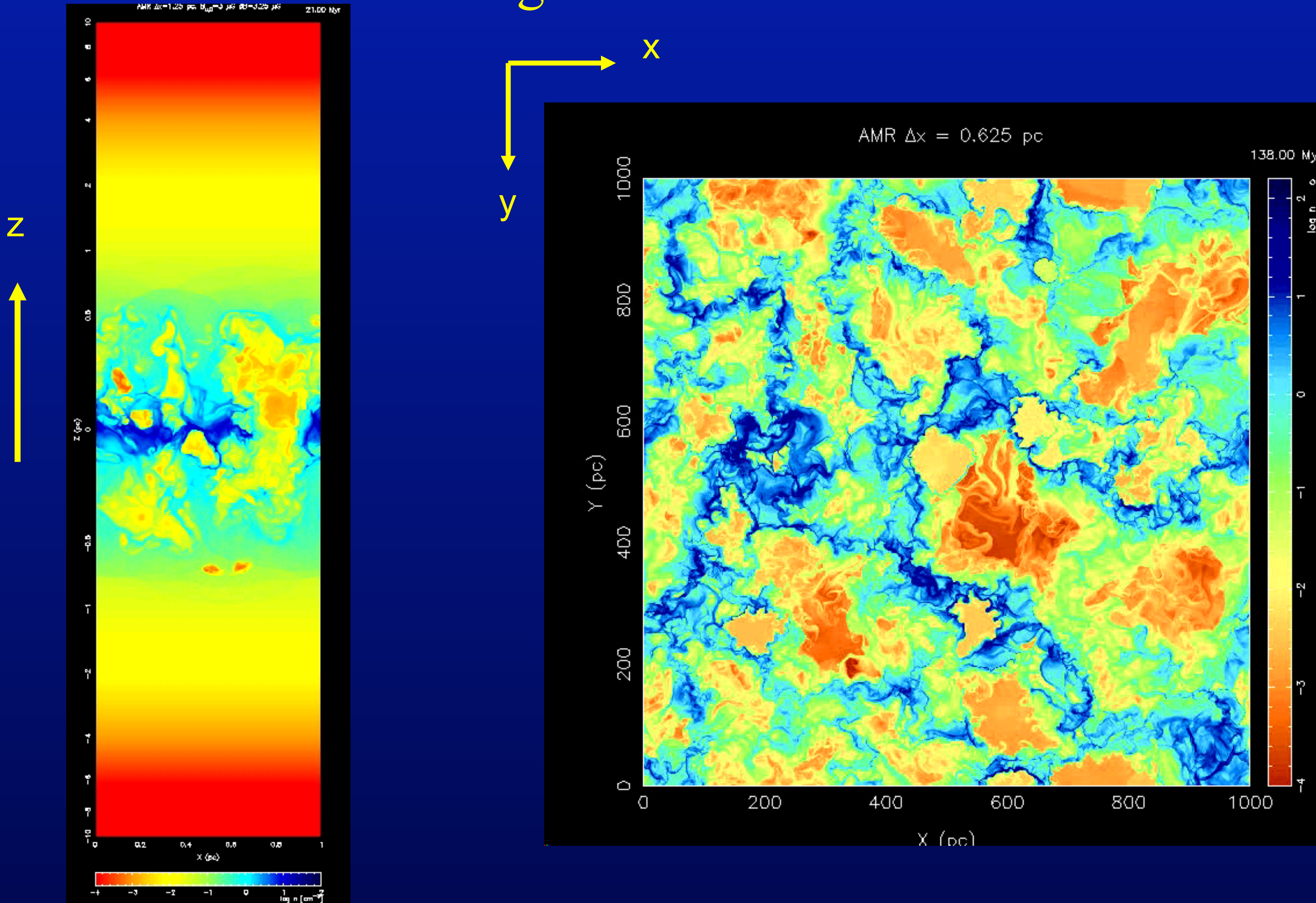
→ formation and motion of OB associations (v_{rms} ~ 5 km/s)

- Evolution of computational volume for τ ~ 400 Myr

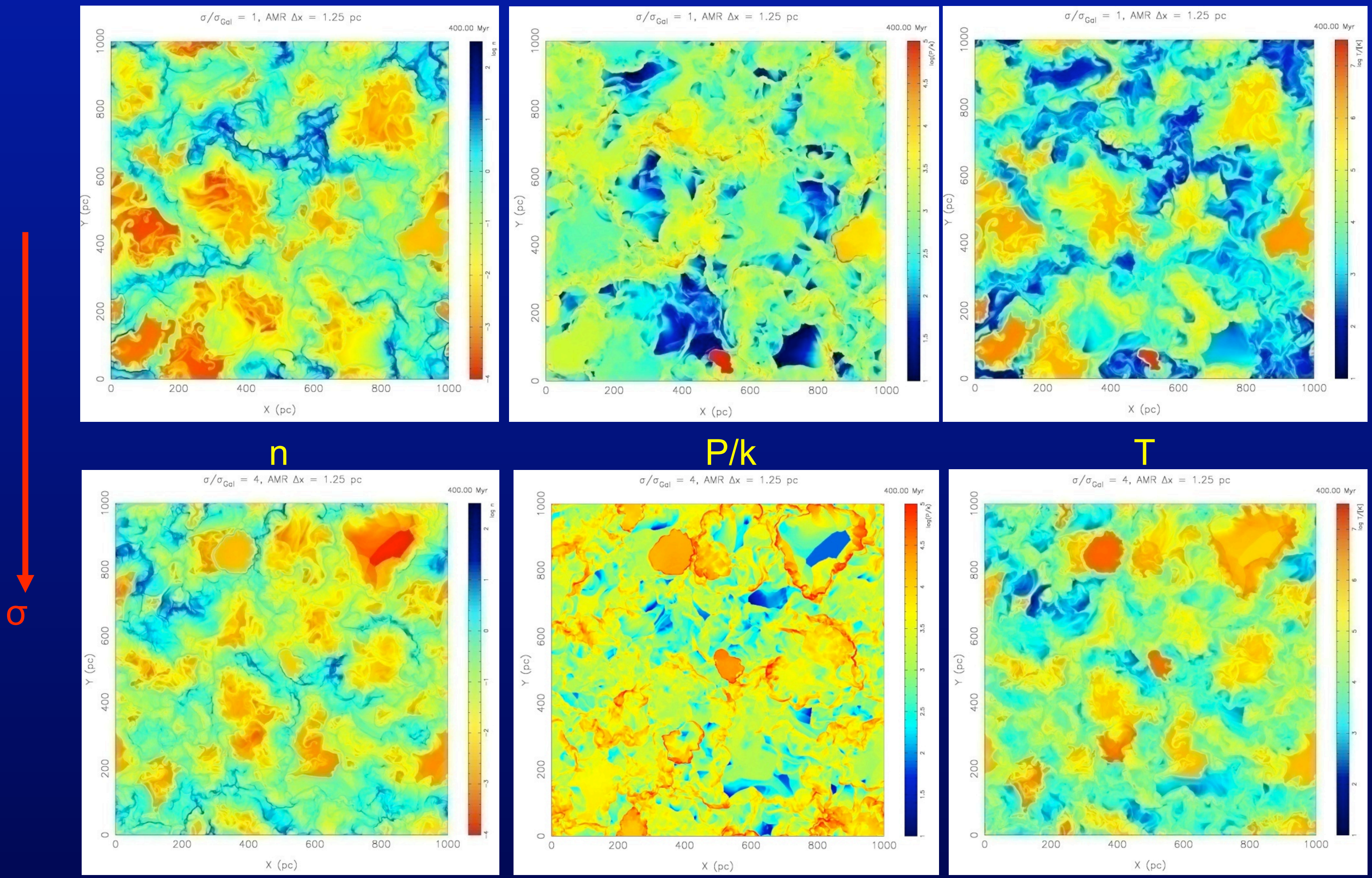
→ sufficiently long to erase memory of initial conditions

- Galactic gravitational field by stars (Kuijken & Gilmore, 1989)
- 3D calculations on parallel processors with AMR

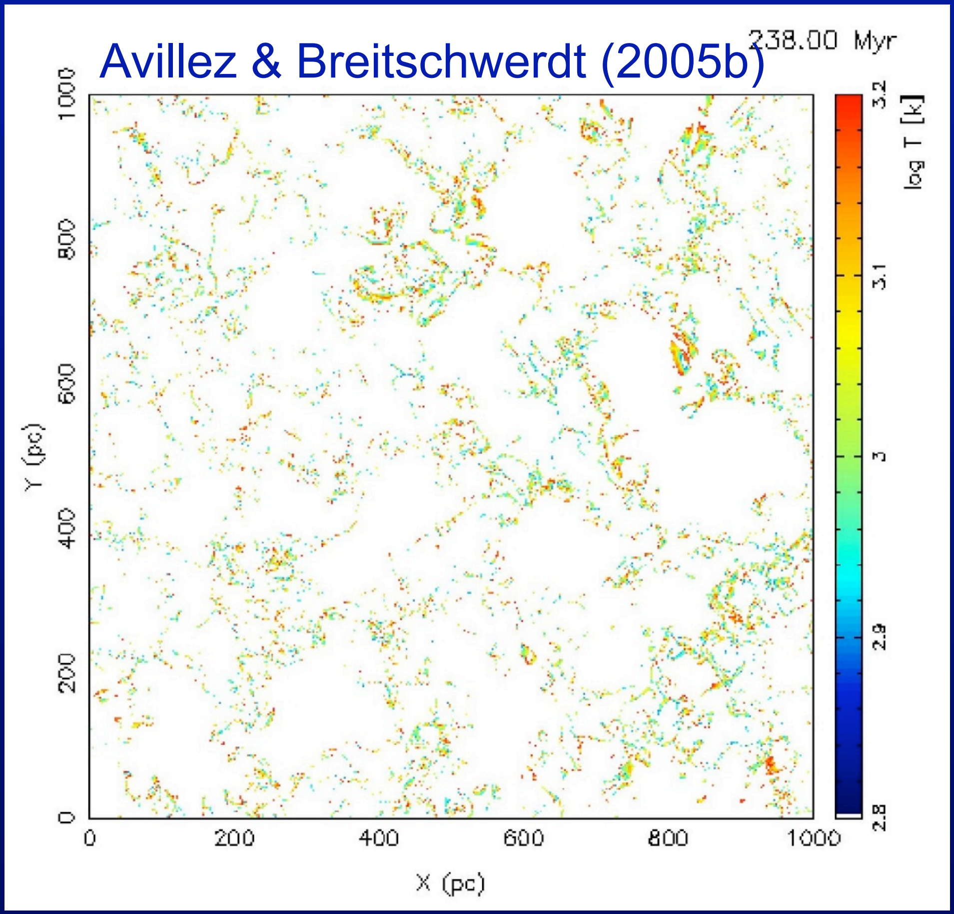
HD Evolution of large/small scale structures of the ISM



2D cuts through 3d data cube (disk cut)



Distribution of WNM in the Galaxy



WNM in the unstable regime $10^{2.8} \leq T \leq 10^{3.2}$ K has filamentary structure
→opposite to MO model
→in agreement with observations (Heiles 2001, Heiles & Troland 2003)

Turbulent diffusion can stabilize!

Results

- P/k far from uniform: spatial structure even for high SN rate ($\sigma/\sigma_{gal} = 4$)
- <P/k> ~ 3000 for Milky Way, i.e. much less than canonical values of > 10,000

  Reason: due to fountain flow, average disk pressure can be lowered
- lots of small scale structure: filaments, shock compressed layers → cloud formation
- turbulence is a key element in ISM structure formation

3. Origin of the Local Bubble - Search for the Smoking Gun

Idea: Cavity AND X-ray emitting gas produced by multiple supernova (SN) explosions

BUT: No OB star cluster INSIDE Local Bubble !

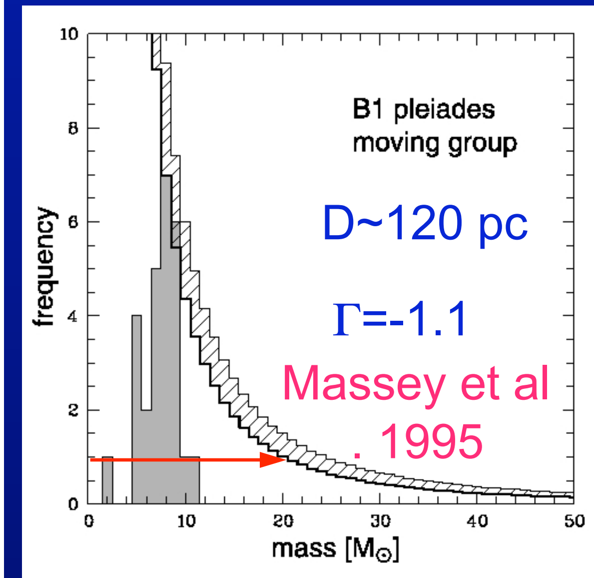
Look for "Smoking Gun":

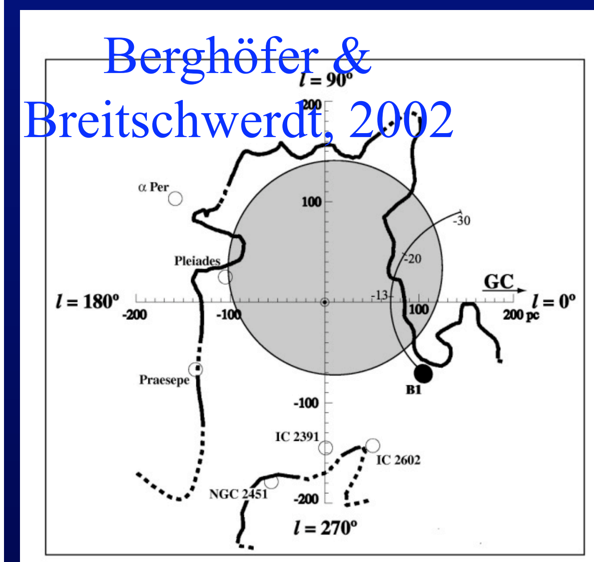
- Moving group (subcluster) of Pleiades found (Berghöfer & Breitschwerdt, 2001, 2002) passing through the LB about 15 Myr ago (s. also Maiz-Appelaniz 2001)

BUT: can we be sure not to have missed stars???

- Search for remnant star cluster in the whole volume around the Sun (∅ ~ 400 pc) using parallactic distances from Hipparcos catalogue and radial velocities from ARIVEL (ARI, HD

a) Moving groups





- Local moving groups (e.g. Pleiades)
- 1924 B-F-MS stars (kin.): *Hipparcos* + photometric ages (Asiain et al. 1999)
- Youngest SG B1: 27 B, $\tau \approx 20 \pm 10$ Myr
- Use evol. track (Schaller 1992):det. M_* , IMF

$$\Rightarrow N(m) = N_0 \left(\frac{m}{m_0}\right)^{\Gamma - 1} (m, m+dm) \quad , \; N(m = 8M_0) = 7 \quad \Rightarrow N(m) = 551.6 \left(\frac{m}{M_0}\right)^{\Gamma - 1}$$

- Adjusting B1-IMF:

$$N(m_{max}) \leq 1 \Rightarrow m_{max} \cong 20\ M_0$$

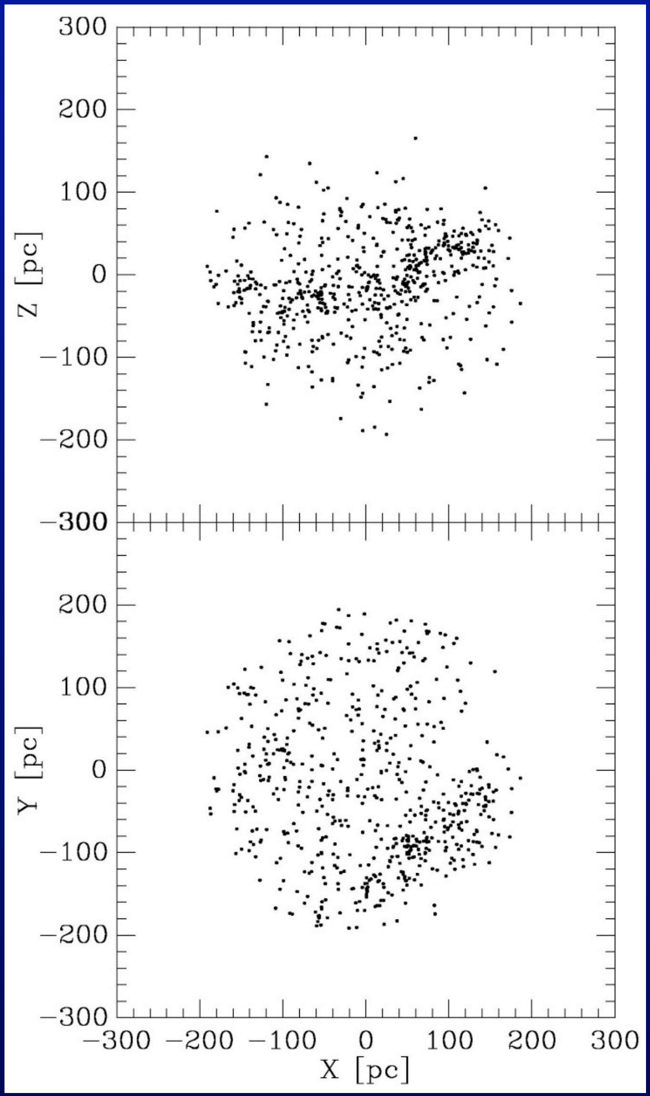
$$\Rightarrow N_{SN} = \int_{m_{min}}^{m_{max}} N(m)\, dm \approx 21$$

b) Complete search of LISM

Selection Criteria I:

- B – V < - 0.05, parallaxes > 5 milliarcsec, earlier than A0, R < 200 pc: 762 stars
- remove subdwarfs (only interested in young stars!)
- search in ARIVEL data base: 610 stars with radial velocities

Young stars in the solar neighbourhood



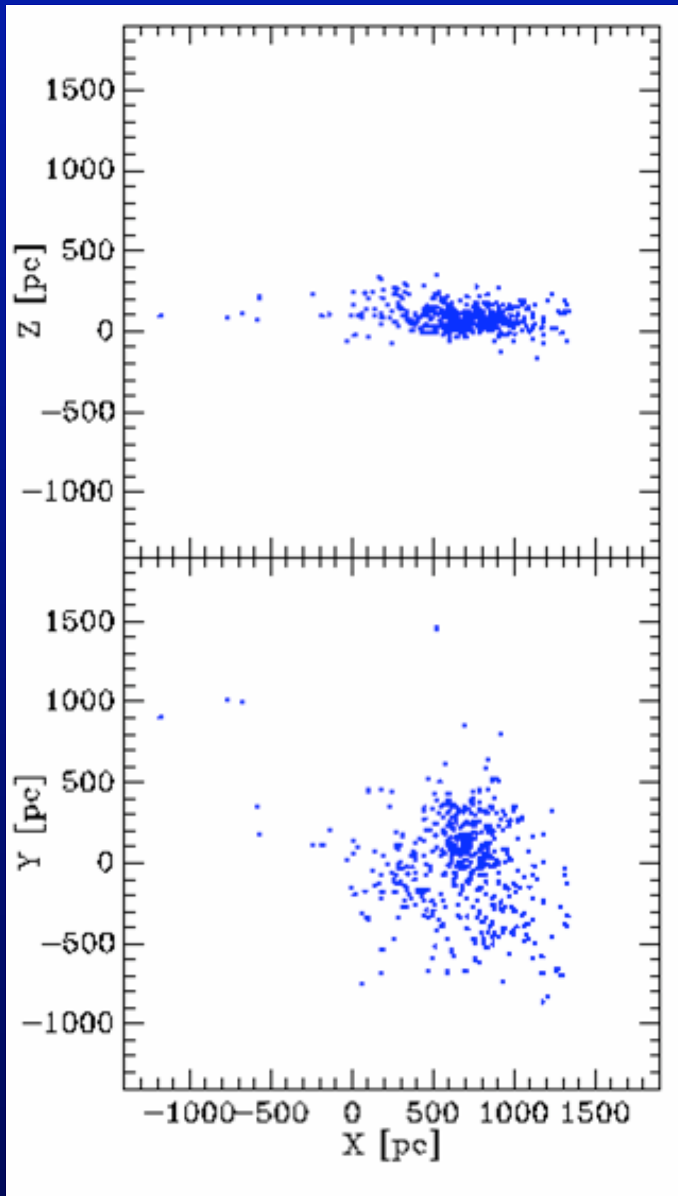
- Positions of 610 stars from Hipparcos and ARIVEL catalogues
- clustering can be seen

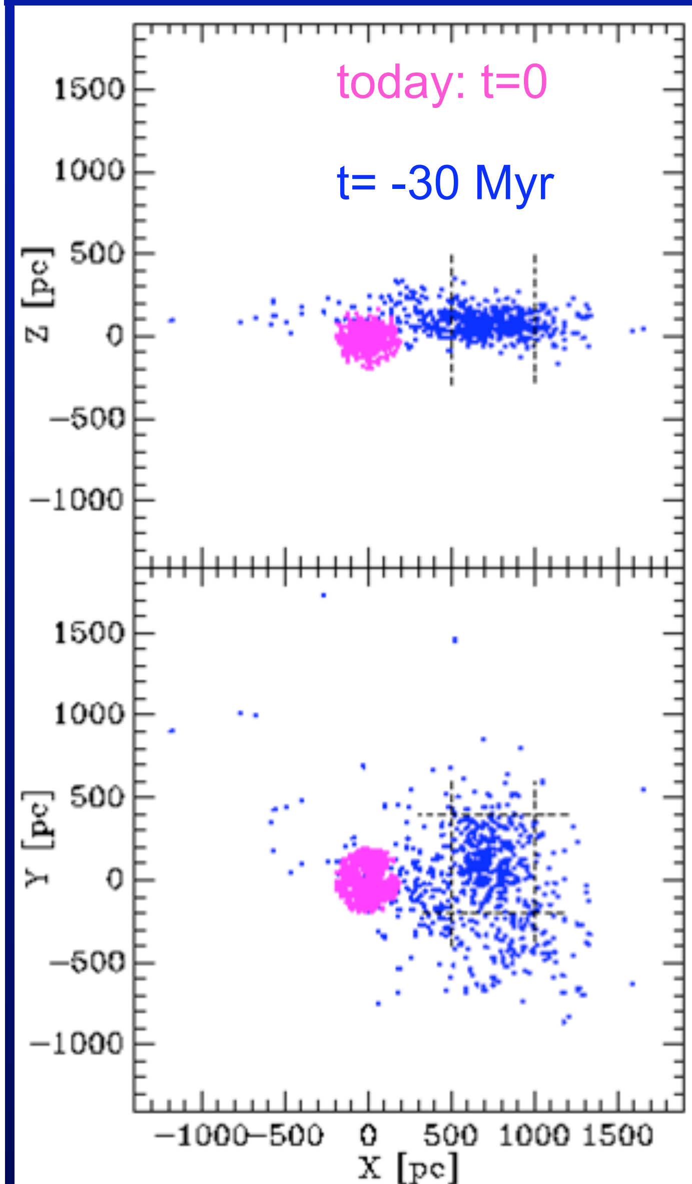
Selection Criteria II:

- OB associations disperse slowly within a few 10^7 yr

  ➡ search for kinematically coherent structures
- tracing the orbits of the stars back in time over 30 Myr

- Solve equations of motion for stars in the gravitational potential of the Milky Way: ➡ "epicyclic equations"
  - X(t) in the radial direction (towards Galactic Centre)
  - Y(t) in the direction of Galactic rotation,
  - Z(t) in the direction perpendicular to Galactic plane

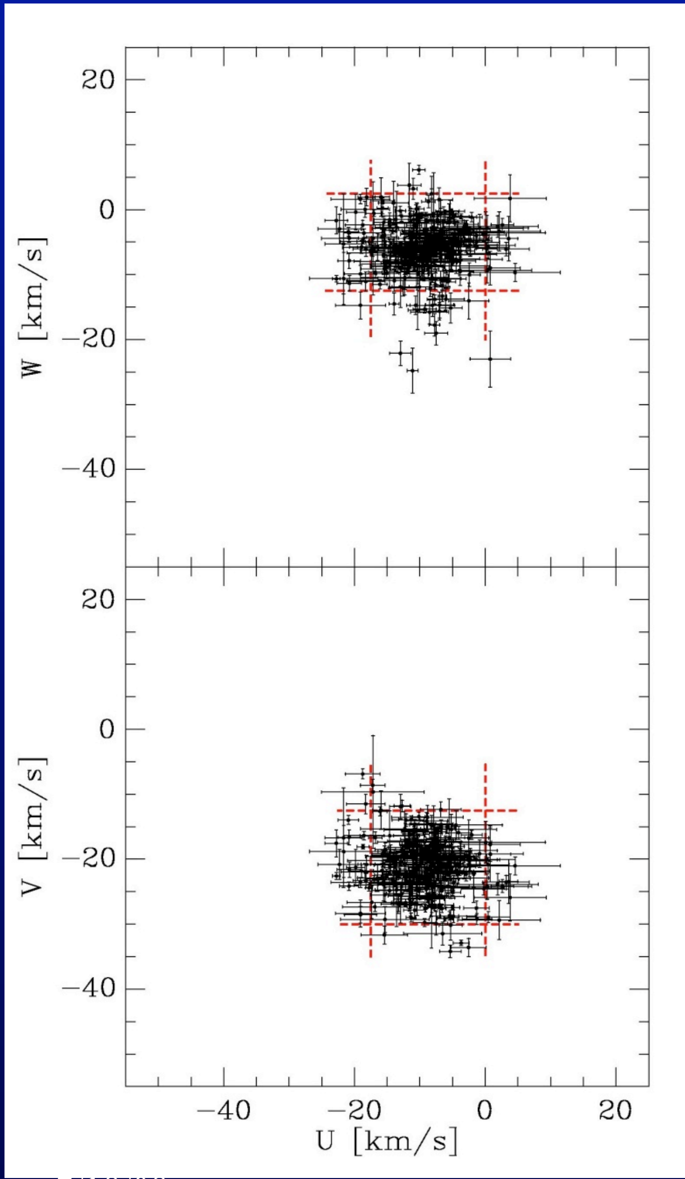




Selection criteria III:

- larger size at t=-30 Myr is due to distance errors increasing with time
- overdense region in past with 302 stars: spatial selection!

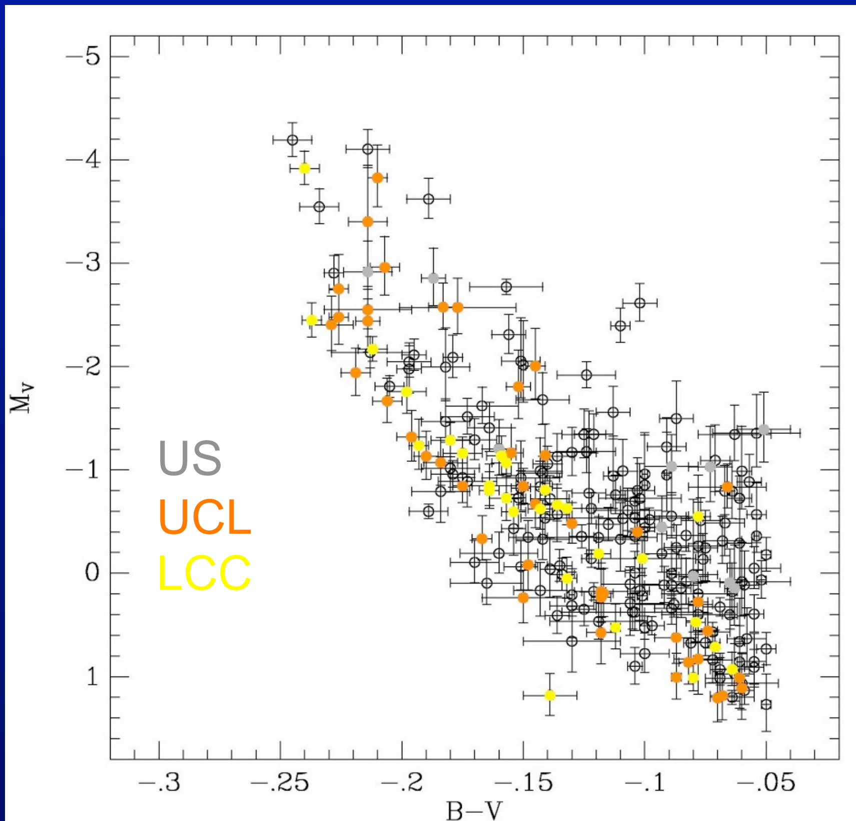
Selection Criteria IV:

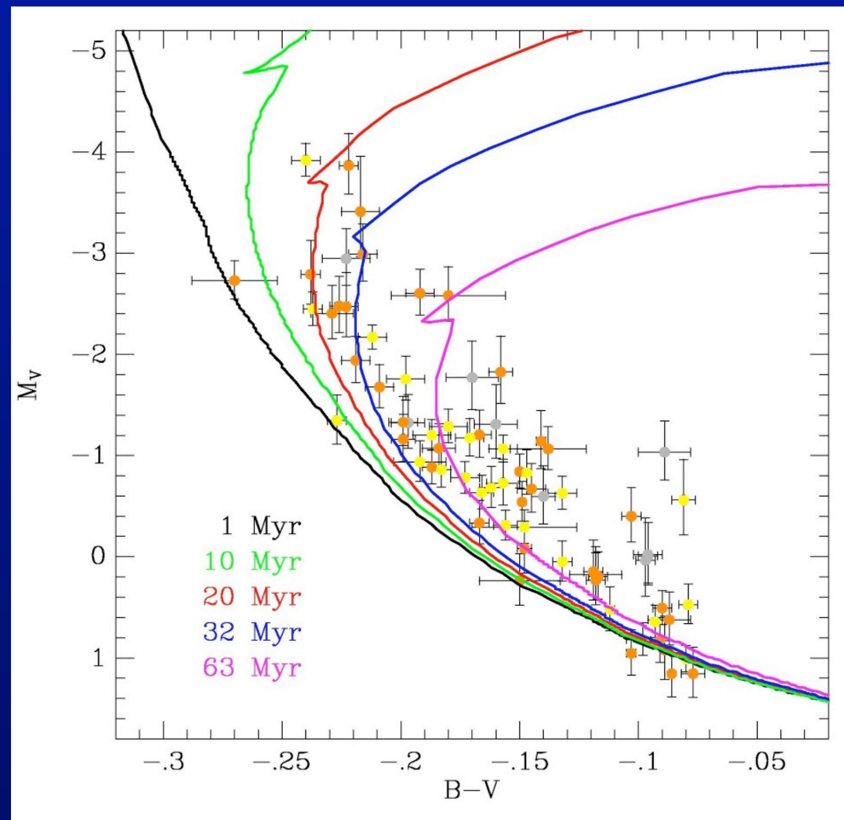


- Present day velocity distribution of 302 selected stars
- Velocity dispersion of OB association is about 10 km/s (Blaauw, 1964)
- Further kinematical selection:

  ➡ exclude stars with higher velocities
- leaves 236 stars for further analysis

Selection Criteria V:





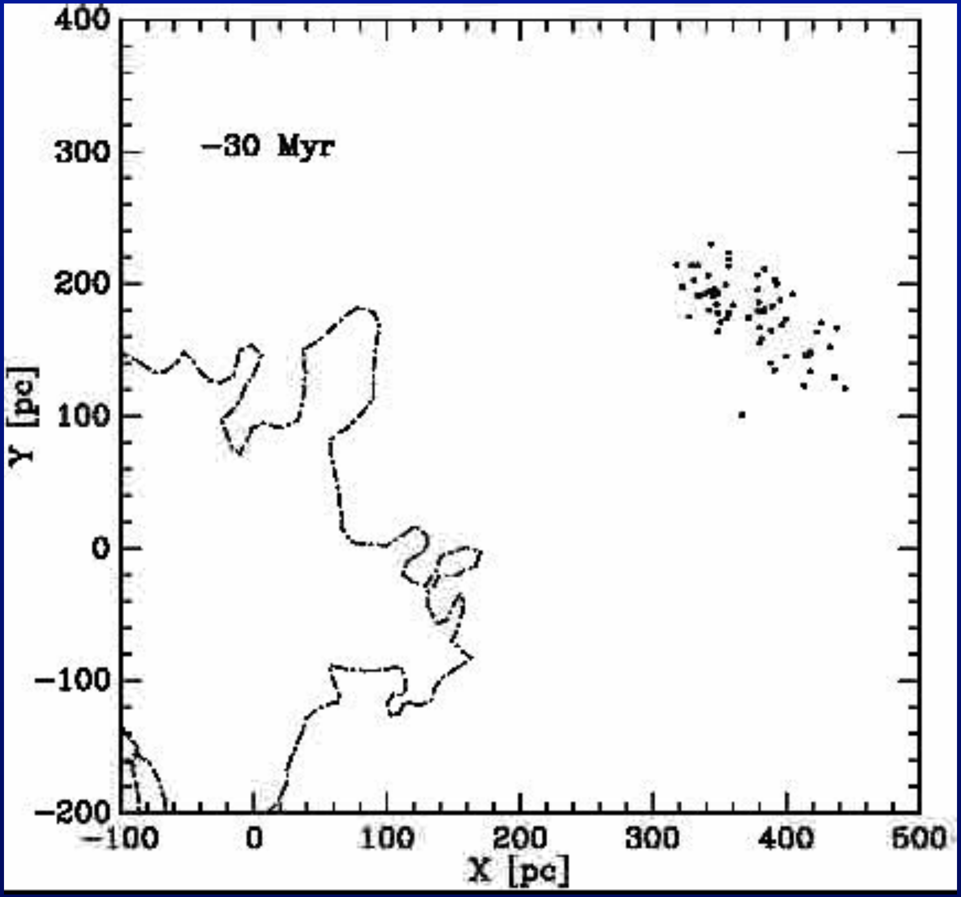
- remove peculiar stars, binaries
- deredden stars

→ youngest stars belong to UCL, LCC, US!!!

- subsample of 73 dereddened stars
- isochrones by Schaller et al. ('92)

→ turn-off from main sequ. age of cluster: 20-30 Myr

Trajectory of youngest nearby cluster



- Path of UCL and LCC stars projected on Galactic plane during last 30 Myr
- use mass-weighted mean velocity of subgroup
- orbits calculated in LSR, since gas has small peculiar motion

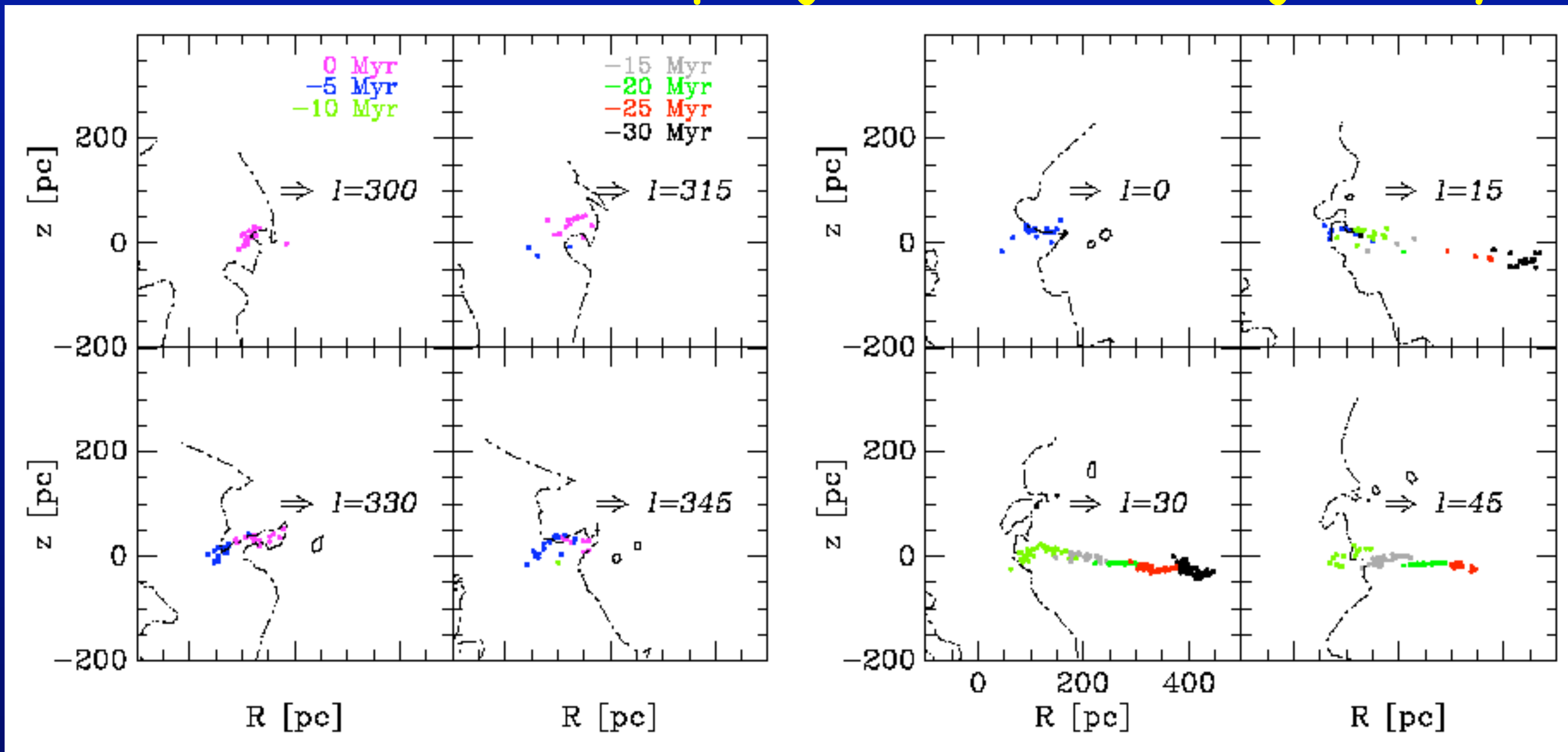
→ LB corotates with LSR

Results:

- at t=-15 Myr path parallel to Galactic rotation

→ SNRs have no shear due to differential rot.

… same for meridional projections of trajectory



- NaI contours taken from Lallement et al.(2003) for present day LB extension
- position of UCL and LCC stars colour coded

Results:

- stars exit LB today (at t=0 Myr)
- stars INSIDE LB at t=-5 & -10 Myr
- stars entered LB at t=-15 Myr (bottom right) ⇒ Origin of LB 15 Myr ago!

How many supernovae created the LB?

IMF: $$\frac{dN}{d\mathcal{M}} = \frac{dN}{d\mathcal{M}}\Big|_0 \mathcal{M}^{-2.1}$$ (Massey et al. 1995)

Number of present day stars in the associations

→ calibrating the IMF!

$$N = \int_{2.6}^{8.2} d\mathcal{M}\, \frac{dN}{d\mathcal{M}}\Big|_0 \mathcal{M}^{-2.1} = 79$$

→ $$\frac{dN}{d\mathcal{M}}\Big|_0 = 302$$ UCL + LCC

Number of supernovae = ``missing´´ stars

$$N_{SN} = \int_{8.2}^{\mathcal{M}_?} d\mathcal{M} \, \frac{dN}{d\mathcal{M}}\Big|_0 \mathcal{M}^{-2.1}$$

Main sequence life time scales with mass as

$$\tau_{ms} = 1.6 \cdot 10^8 \,\mathrm{yr} \left(\frac{\mathcal{M}}{\mathcal{M}_\odot}\right)^{-0.93}$$

Entry of the associations into present bubble volume between 10 and 15 Myr ago:

→ $M_? = 15.4\ M_{sol}$ → 14 SNe

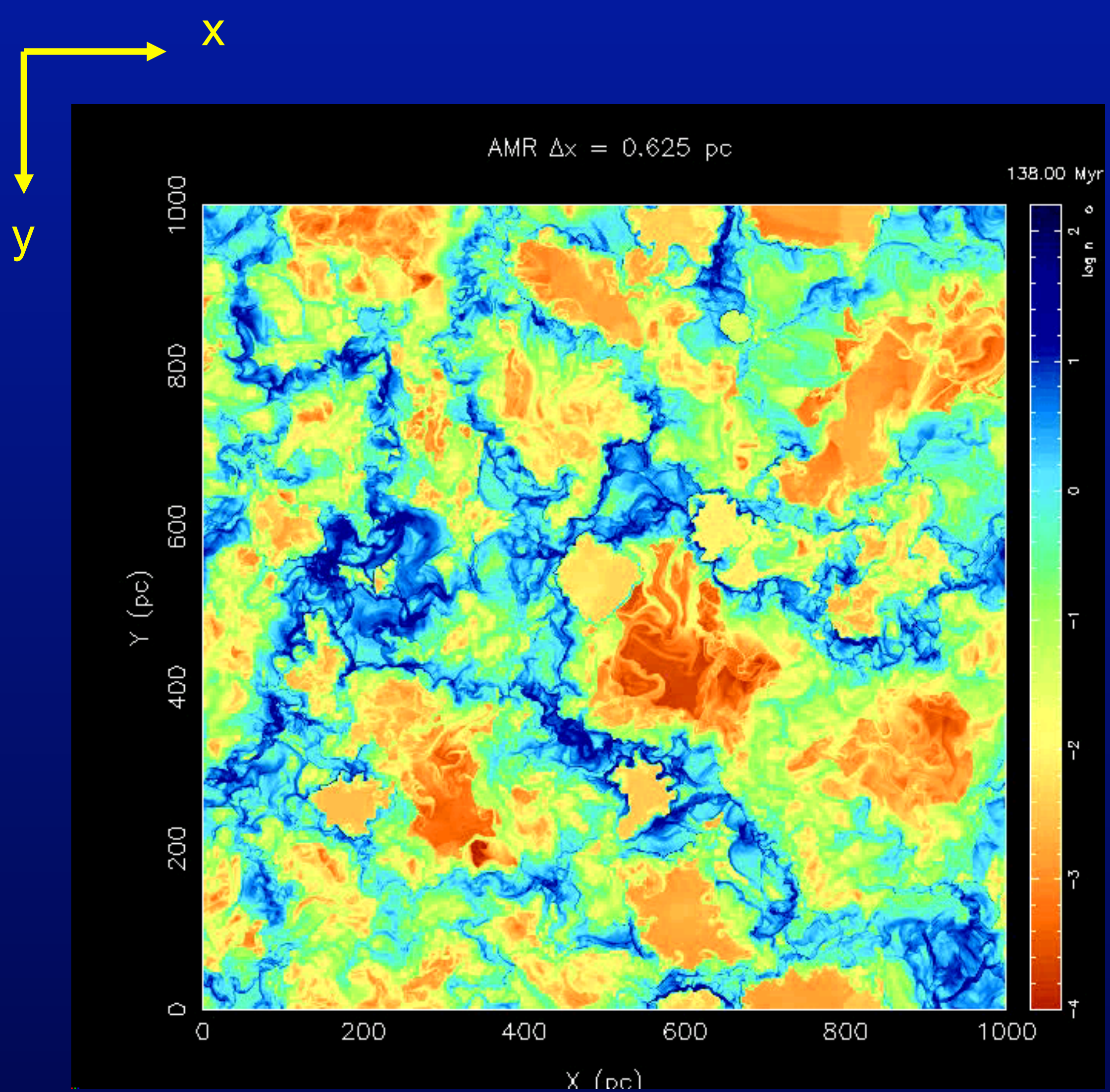
$M_? = 26.6\ M_{sol}$ → 20 SNe

→ good agreement with Berghöfer & Breitschwerdt (2002)

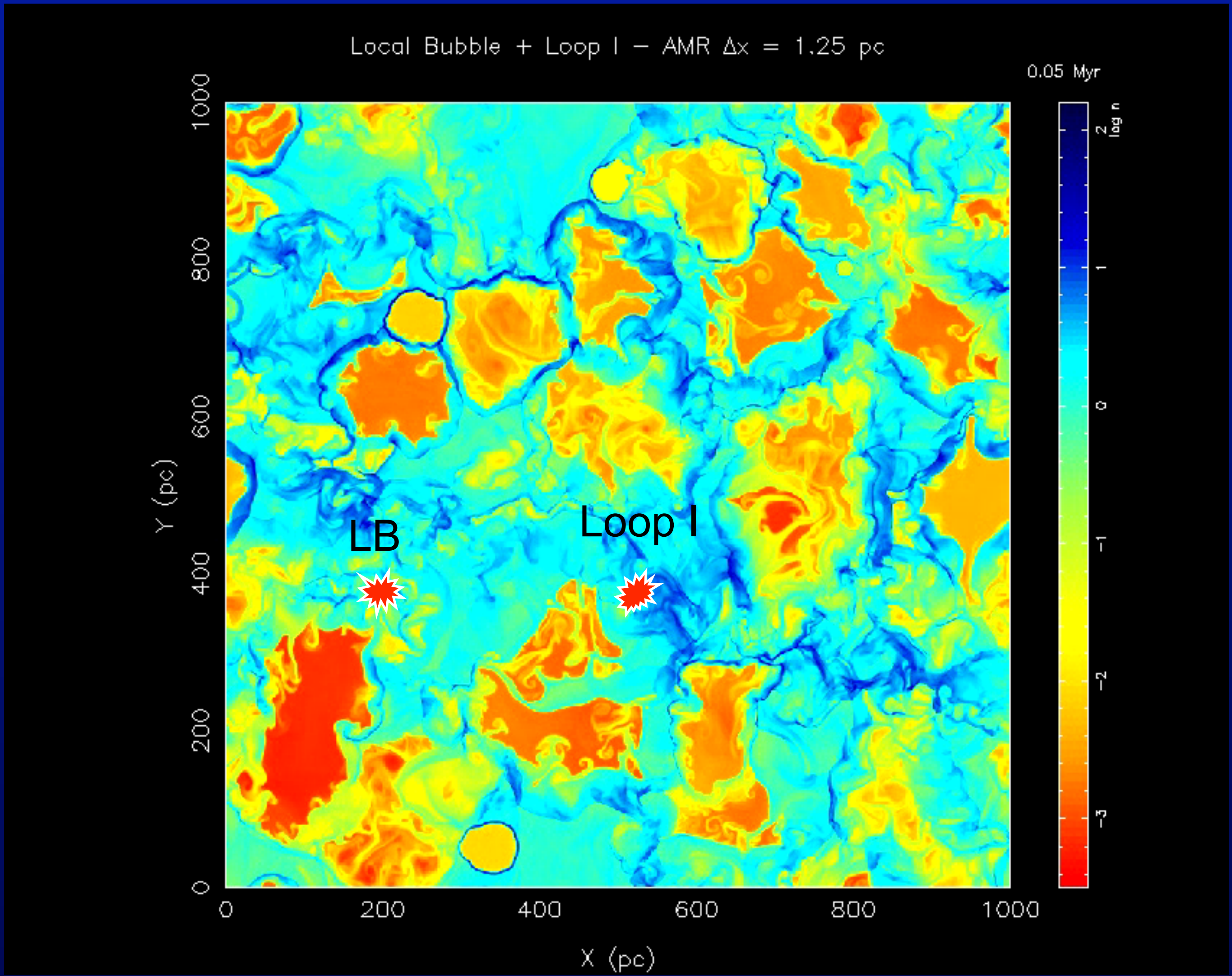
Numerical Modeling

- Solve full-blown hydrodynamic equations in a ***realistic environment!***
  - Local Bubble expands into ambient medium which was disturbed by SNe & Superbubbles at Galactic rate over ~ 100 Myrs
  - Local Bubble & Cavity generated by 19 SNe according to IMF
- 3D calculations on parallel processors with adaptive mesh refinement (AMR)

Disturbed background ambient medium



3D AMR Simulations



- Density
- Cut through galactic plane
- LB originates at (x,y) = (200 pc, 400 pc)
- Loop I at (x,y) = (500 pc, 400 pc)

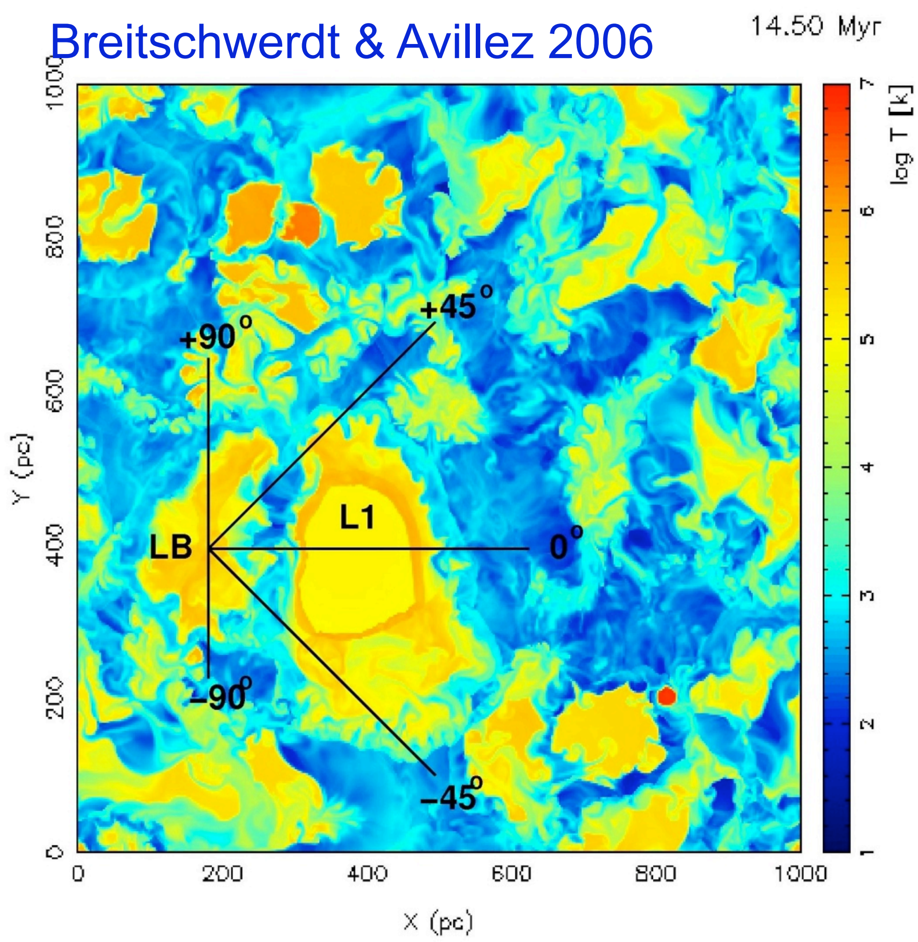
Results

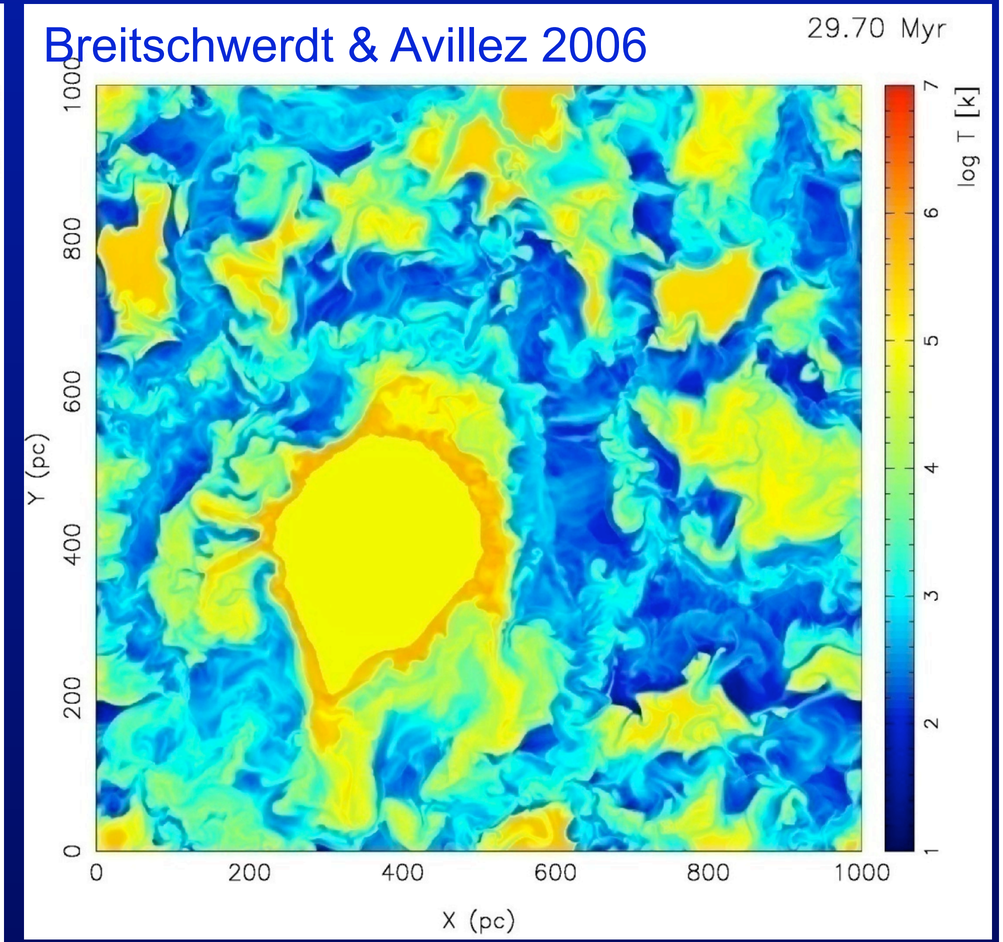
Bubbles collided ~ 3 Myr ago

Interaction shell fragments in ~3Myrs

Bubbles dissolve in ~ 10 Myrs

The Local Bubble: Now and in the Future

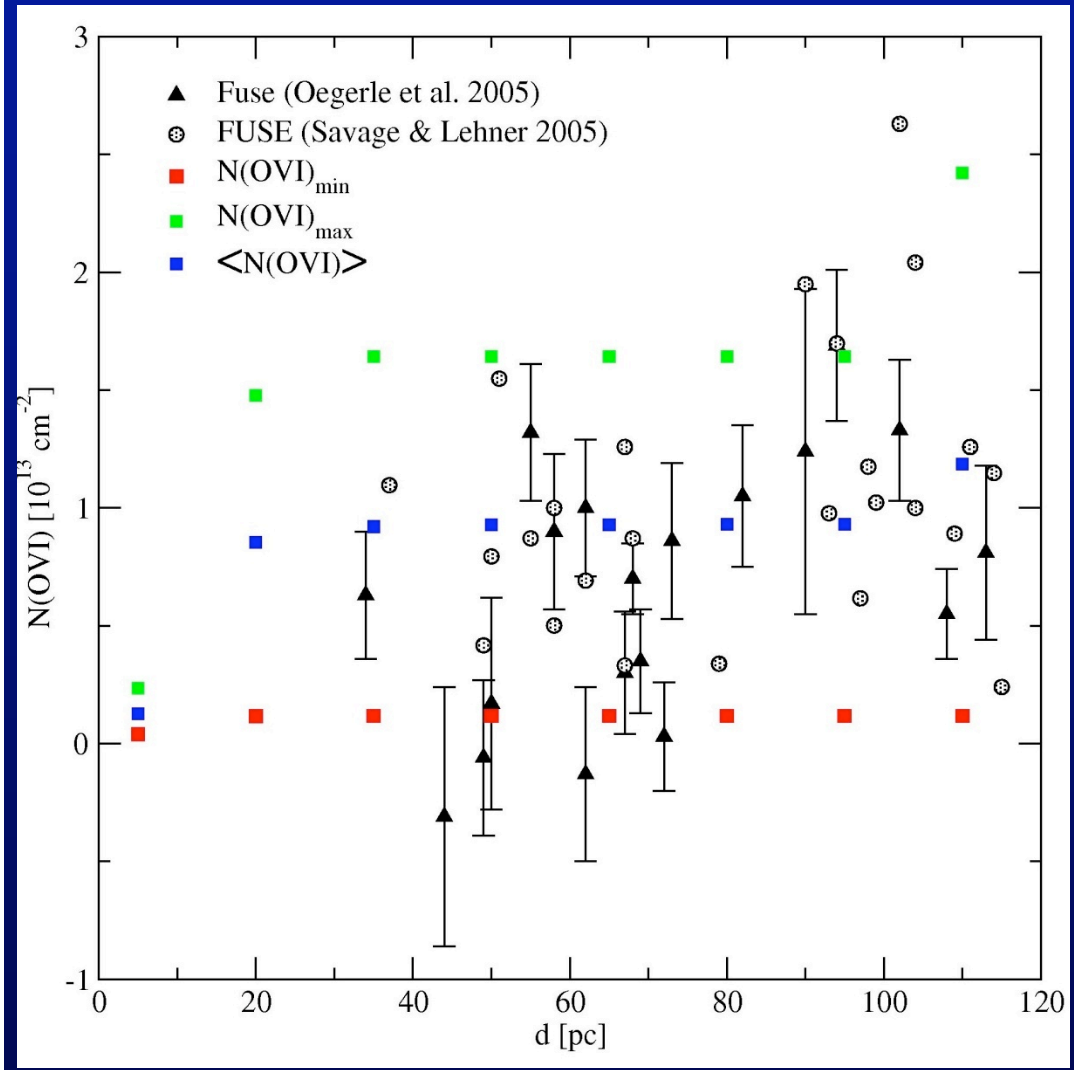




- LB is extinct: last SN 0.5 Myr ago
- LB age: 14.4±0.7/0.5 Myr

- Interaction shell LB/Loop I breaks
- Overflow of gas into recombining LB

Comparison with UV-Observations

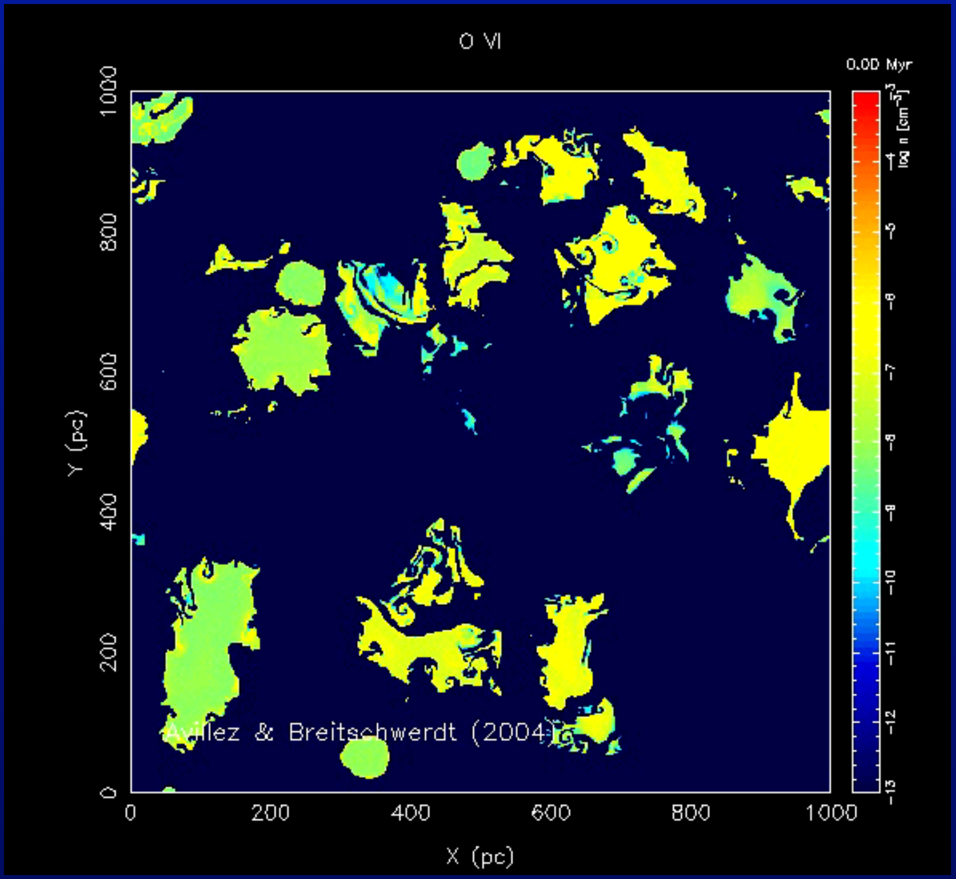


- OVI column densities from simulations averaged over 91 L.O.S. towards Loop I
- Direct Comparison with FUSE satellite date

excellent agreement!

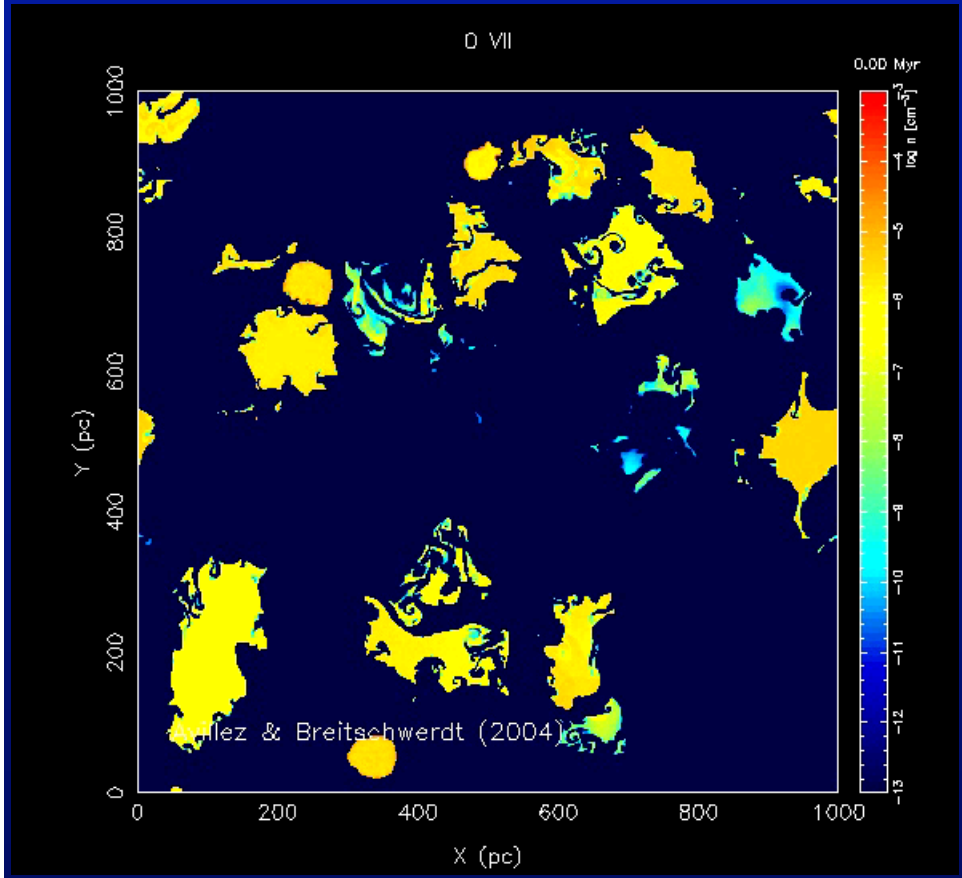
- Previous models produced too much OVI!

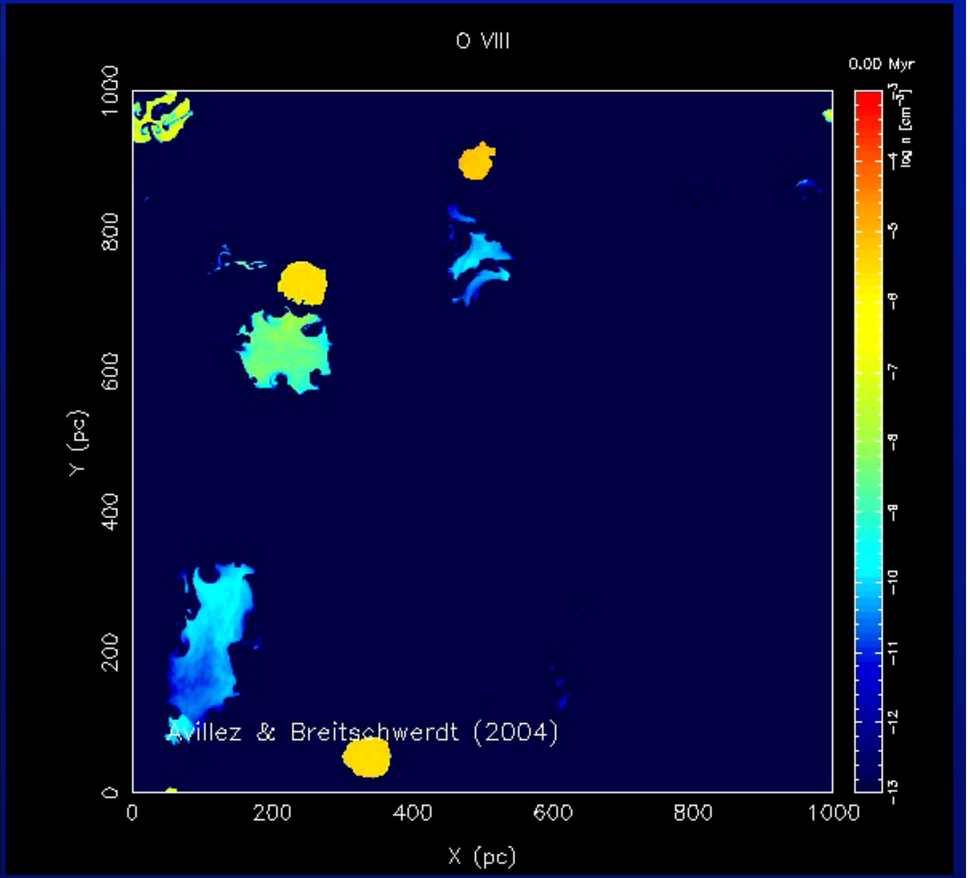
OVI Column densities



- Crucial test for LB models (Cox 2003)
- Reason: previous SNR and SB models generate 10–100 times too much OVI in absorption towards back-ground stars
- Possible solution:
  - ➢ LB is old and has complex temperature structure
  - ➢ Hot gas highly turbulent
  - ➢ Ambient medium inhomogneous

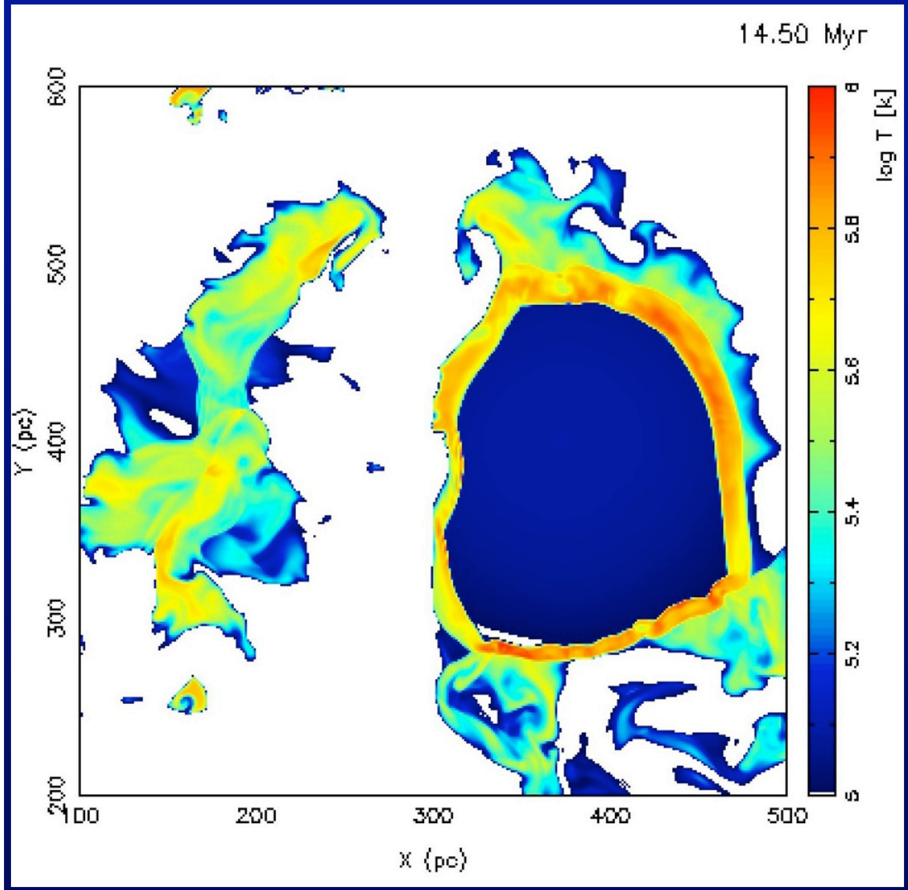
… and OVII and OVIII

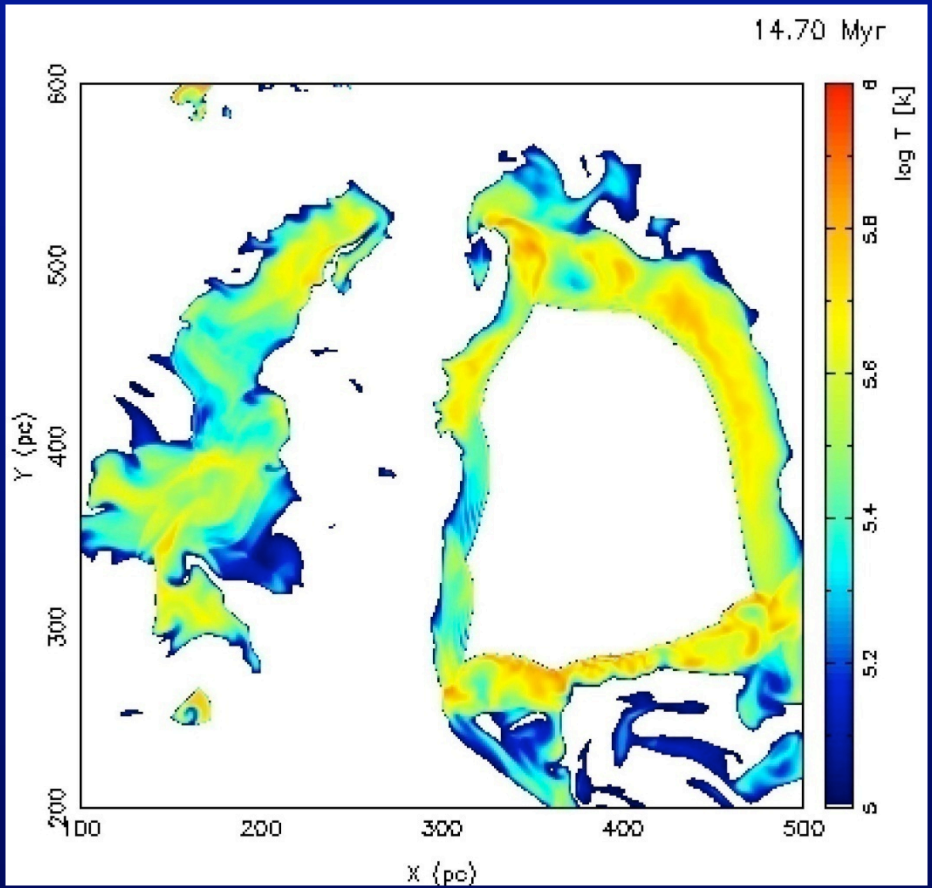




- OVII traces hot gas during ongoing SN activity
- OVIII is post-supernova tracer
- Loop I higher activity: more OVIII

Coexistence of UV absorbing and X-ray emitting gas





LB in temperature filter 10^5 K < T < 10^6 K

Summary & Conclusions

- Solar system embedded in void of HI filled with X-ray emitting gas
- X-ray plasma does not fill Local Cavity completely
  → spectrum inconsistent with gas in CIE (cf. XQC, CHIPS ...)

- Huge pressure imbalance between LB (P/k ~ 15000, Snowden 1998) and Local Cloud (P/k ~ 1700 - 2600, Lallement 1998) and other clouds (P/k ~ $10^3 – 10^4$, Jenkins 2002) inside the LB
- OVI absorption column density in previous models 10 times higher than observed → our simulations reproduce FUSE data

- Fast adiabatically expanding plasma due to superbubble evolution
→ ionization and recombination are out of equilibrium
→ delayed recombination produces spectrum roughly in agreement
→ solar wind charge exchange may contribute as well

Which physical processes are at work in the Local Bubble?

- Local Bubble (and Loop I) are typical objects in star forming regions → LB is evolved and recombining superbubble
  → Loop I evolution is still in full swing
- LB breaks out into halo
- LB radiates in UV and soft X-rays for some time
- Turbulence is a key process for LB dynamics and evolution!

Origin of the Local Bubble/Cavity probably solved!

- subgroups belonging now to Sco Cen association crossed LB region ago 10 – 15 Myr
- 14 – 20 SN explosions created LB Cavity, X-ray and OVI emission
- LB has age of 14.5 Myr
- LB will dissolve in about 15 Myr
- LB/Loop I interaction shell will fragment in 3 Myr
- LIC and local clouds are relics from instability of interaction shell

3 D AMR high resolution numerical simulations:

- Modelling of LISM (LB+ Loop I) in realistic (SN modified) background medium → good agreement of LB/LI extensions

→ pressure problem also solved: P/k ~ 2000 K cm^{-3}!

- especially useful for describing old bubbles with density inhomogeneities and mass loading of entrained clouds

→ possible to reproduce OVI absorption column densities

→ generation of local cloudlets by RT instabilities

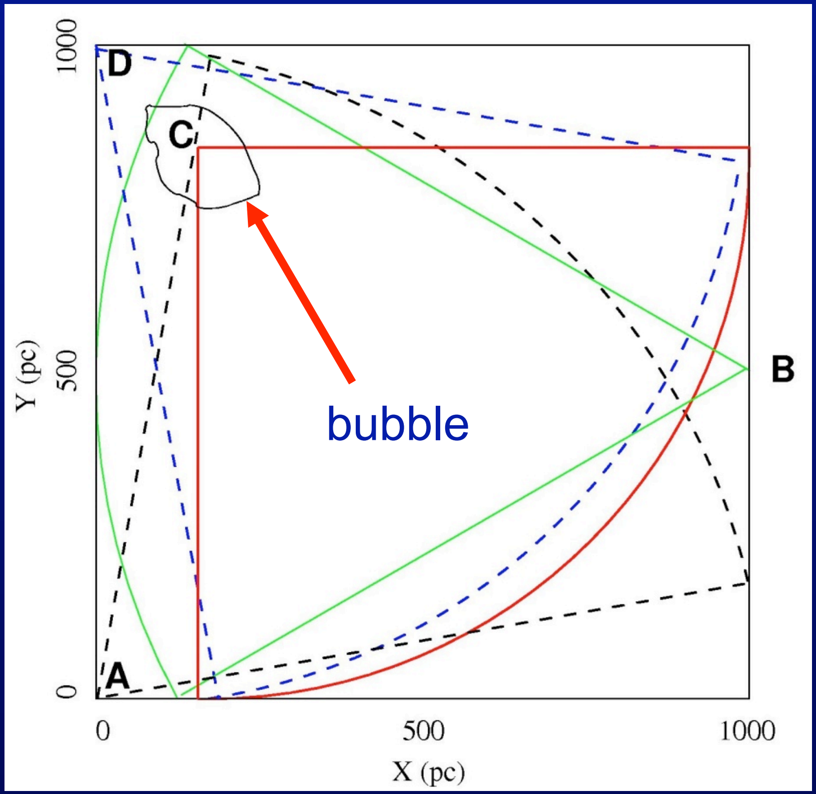
Future Work:

- Numerical modelling of LB including full non-equilibrium ionization (NEI) cooling and emission!
- Model X-ray emission and compare to observations
- Determine time-dependent cosmic ray flux during last 30 Myr

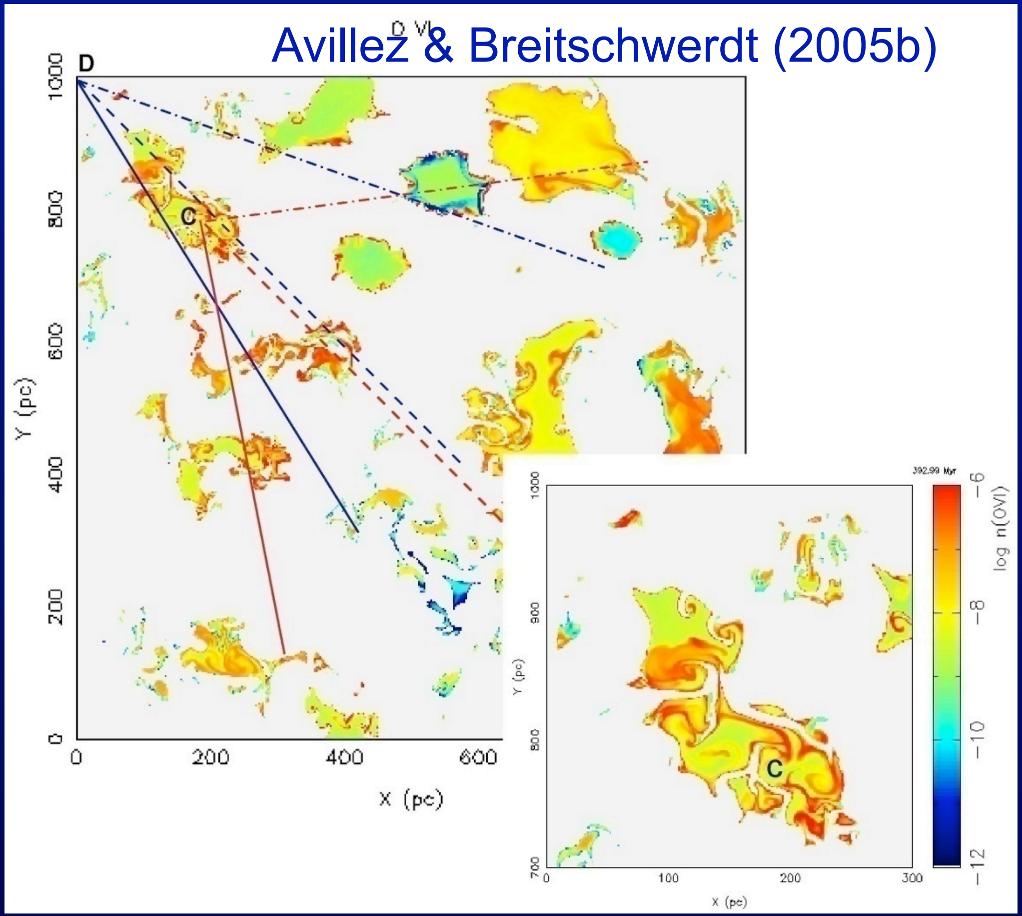
- The End -

The OVI test: The General ISM

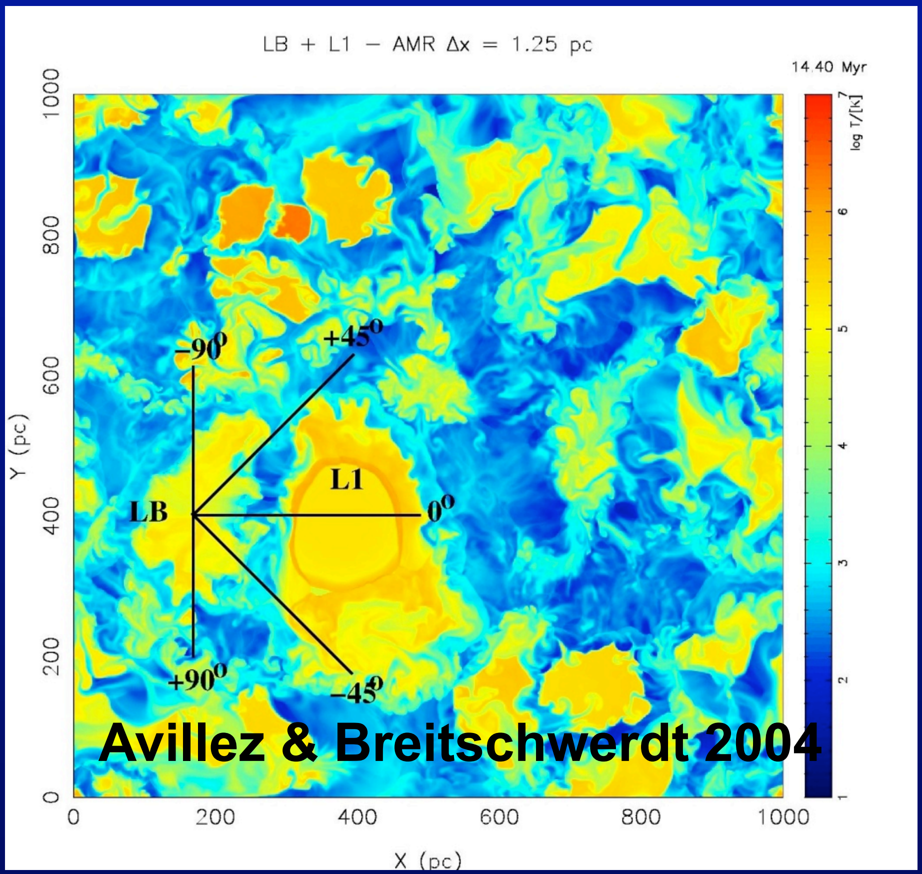
- OVI traces (cooling down) HIM, not soft X-ray emitting gas!
- OVI produced in conduction fronts? efficiency rather high!
- our simulations show: OVI in turbulent mixing layers!

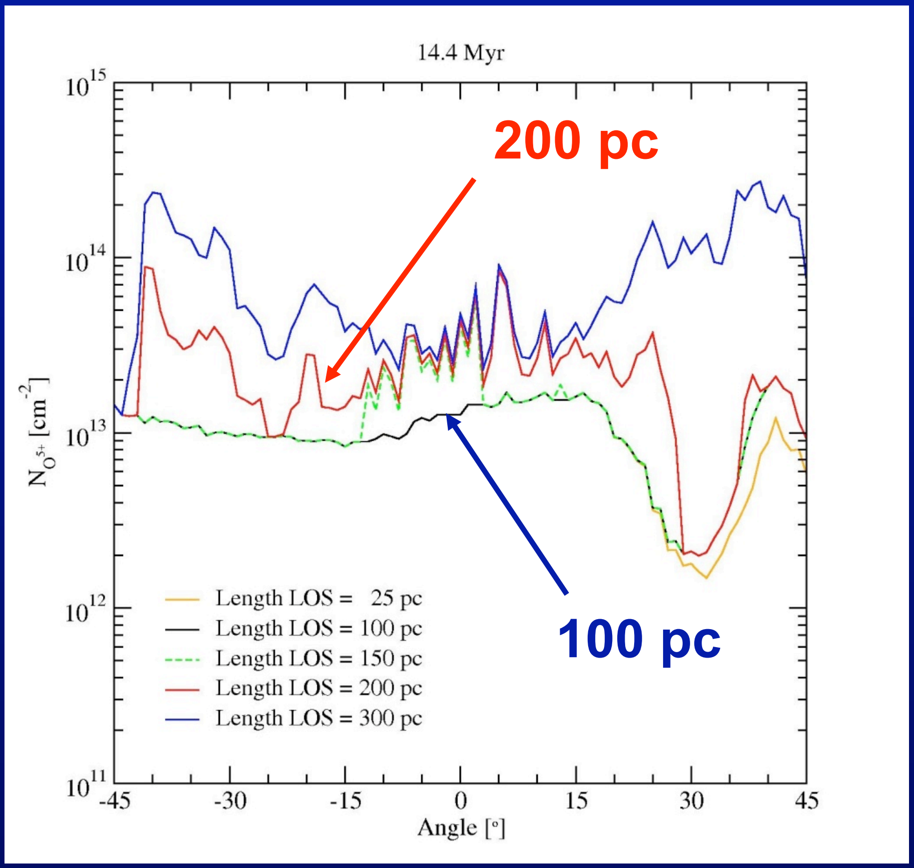


Avillez & Breitschwerdt (2005b)

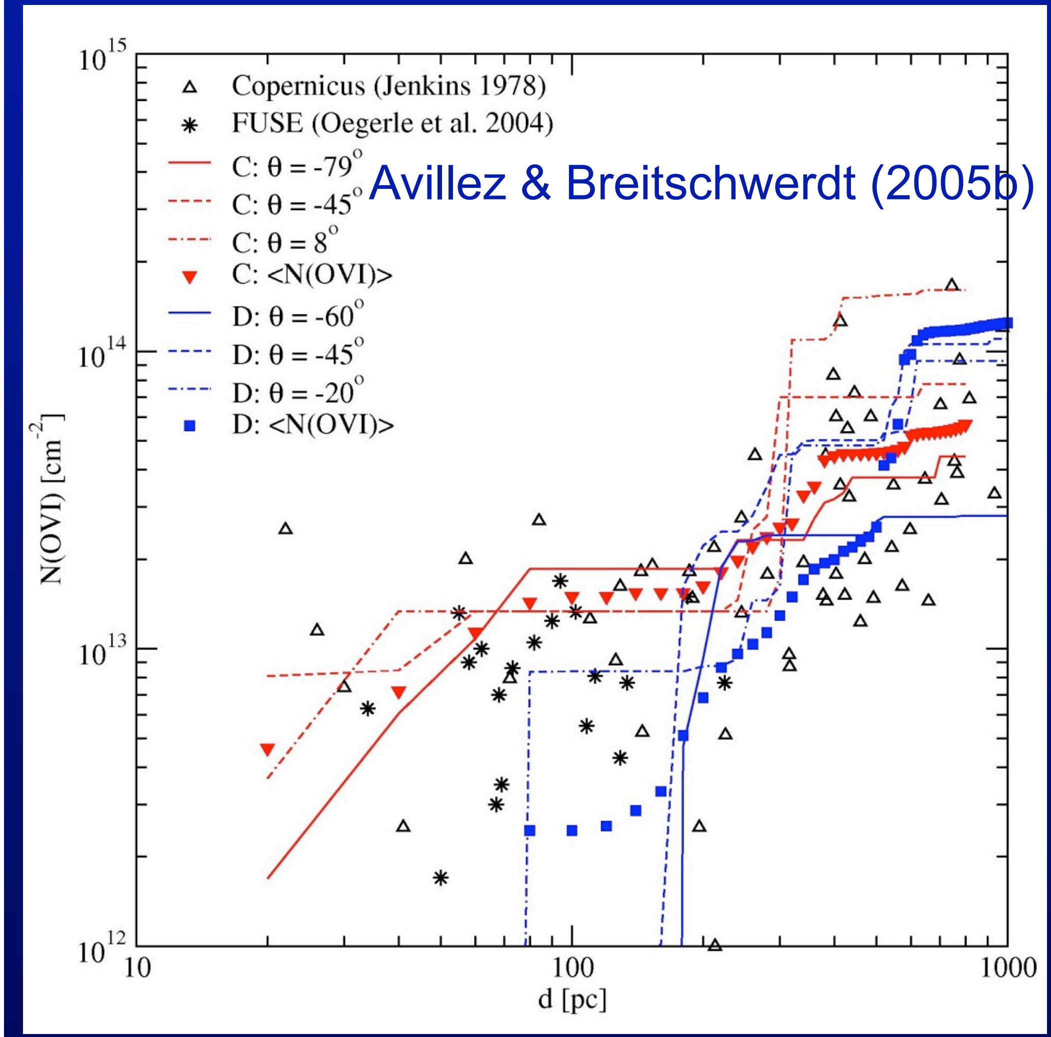


N(OVI) through Local Bubble sight lines



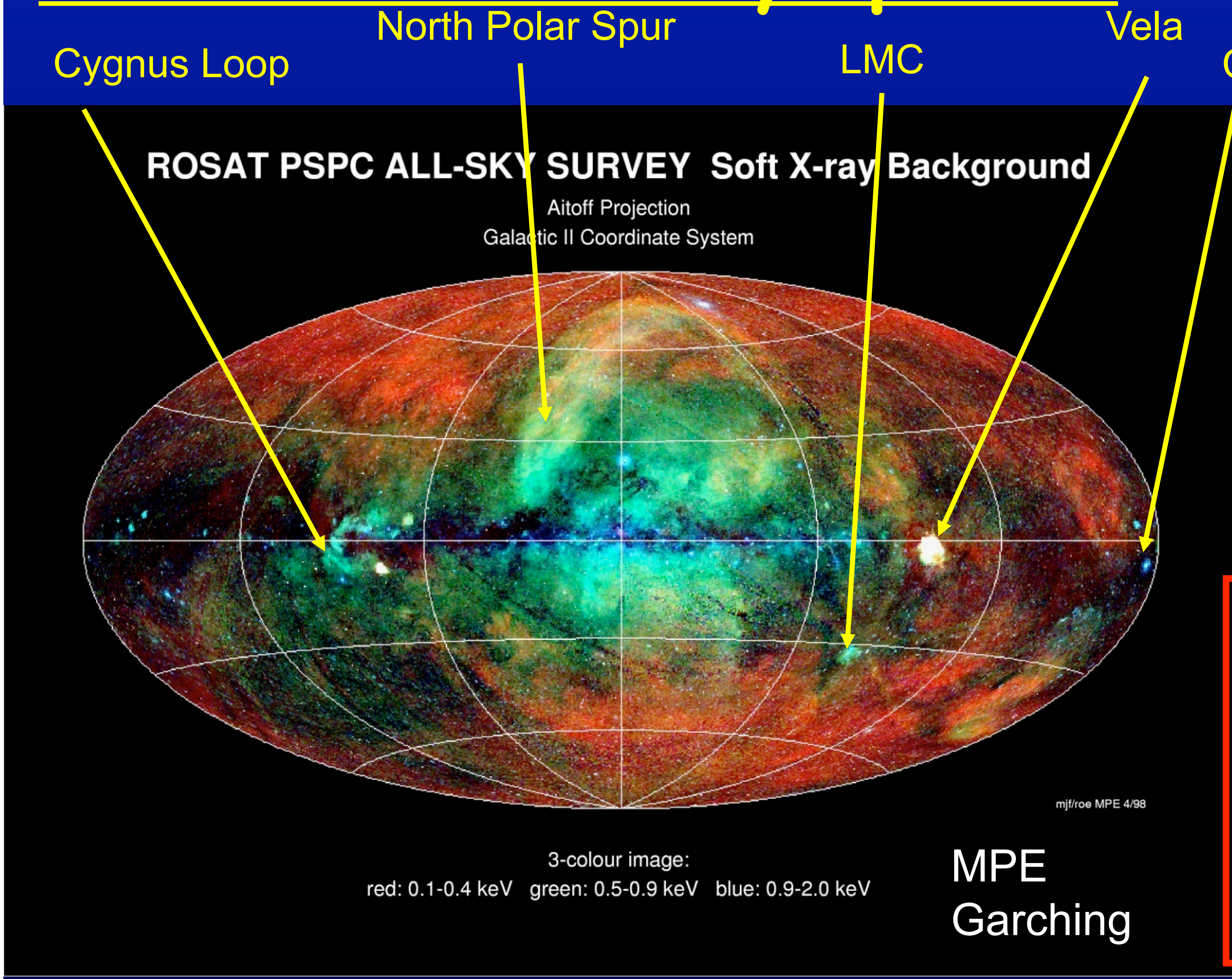


- Temperature map at t=14.4 Myr
- Sampling OVI in absorption
- <N(OVI)> at l=200 pc: $\sim 2\times10^{13}$ cm^{-2}
- Copernicus data: $\sim 1.6 \times 10^{13}$ cm^{-2} (Shelton & Cox 1994)



- FUSE & Copernicus data of OVI absorption lines towards background stars
- comparison with simulations (run for t = 393 Myr): spatially averaged (red triangles, blue squares) and single LOS N(OVI)
- ISM has a pattern, repeating on scales of a few 100 pc!
- **Note:** simulations were done before data of Oegerle et al. (2004) were published!
  No "tuning" of results!

Local Bubble X-ray spectra

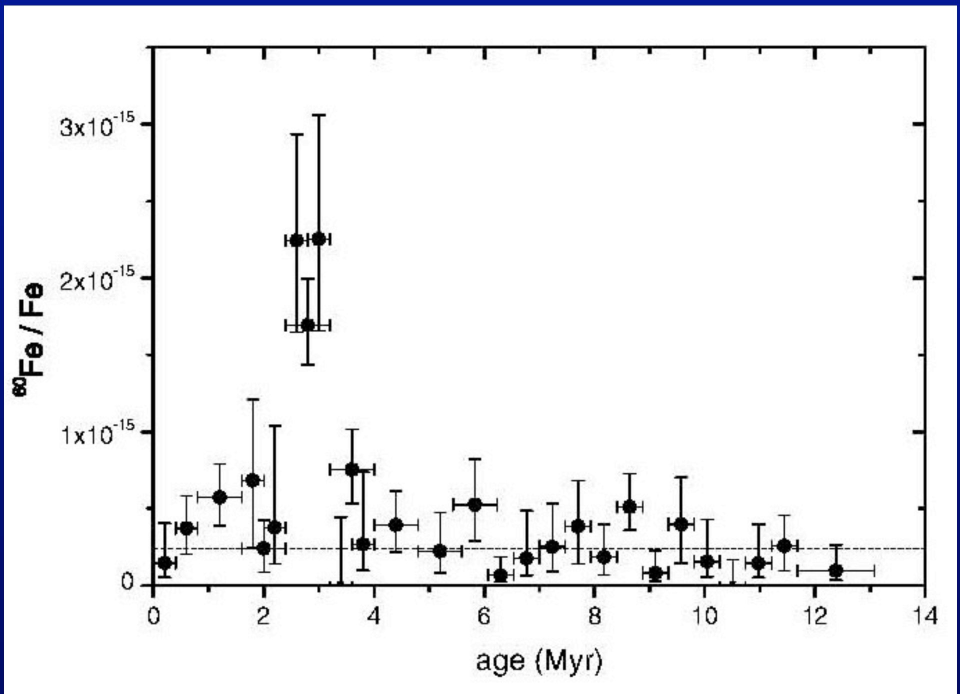


Where does Local Cavity come from?
→ Talk by Lallement!

What produces X-ray emitting Plasma?

Supernovae could create a local hole
- *Local Bubble!*
- contribution by solar wind charge exchange

When and where did the last Supernova close to Earth occur?



- Measurement of ^{60}Fe/Fe concentration in deep sea ferromanganese crust (Knie et al. 2004)
- dominant source of ^{60}Fe is explosive nucleosynthesis in Type II SNe
- significant increase at t = -2.8 Myr

consistent with closest approach to Earth of our moving group